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Charge discharge standpipes at Hunterston

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND

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COVER PICTURE

View underneath the spherical pressure vessel for reactor A at Hunterston Nuclear Generating Station, showing some of the 101 charge discharge standpipes in position prior to final welding. The tops of the matching standpipes in the 6 ft-thick bottom biological shield can also be seen.

The stained glass mural in the Reception Hall of the new Headquarters of Arthur Sanderson & Sons Limited, London, was designed by John Piper and executed by Patrick Reyntiens and symbolizes the purpose of the new building, the largest ever constructed for presenting new ideas and materials for interior decoration.

It is illuminated from behind by Osram cold cathode tubing arranged in special G.E.C. lighting fittings.

Friction Winder at a South African Gold Mine

By C. MEYER, A.M.I.Mech.E., M.S.A.I.Mech.E., Chief Mechanical Engineer,
and C. B. READ, M.A.(Cantab.), A.M.I.Mech.E., A.M.I.E.E., A.M.(S.A.) I.E.E.,
Engineering Department, B.G.E.C., Johannesburg.

FOR many years the gold-fields of the Witwatersrand consisted of a more or less continuous line of mines spread out over a length of about fifty miles from Krugersdorp in the west to Springs in the east, and it was thought that the gold-bearing reefs extended no further. In 1930, however, geophysical surveys carried out on the recommendation of Dr. Rudolph Krahmann, an eminent geophysicist, with the active support of G. Carleton-Jones of New Consolidated Gold Fields Ltd., indicated the presence of the basal shales of the Witwatersrand series of rocks to the south-west of Krugersdorp. A company named West Witwatersrand Areas Ltd., was organized in 1932 to explore and develop the area, and a series of boreholes were drilled. These led to the discovery of gold-bearing reefs, some very rich, at a number of points extending for fifty miles or so beyond Krugersdorp on what became know as the 'West Wits Line.'

It should be added that similar geophysical surveys carried out subsequently have led to the opening up of mines still further south-west in the Klerksdorp area and to the development of a new gold-field in the Orange Free State with reefs of the same geological series, some of which seem likely to be even richer than those on the West Wits Line. More recently, this astonishing formation of rocks has been traced eastwards as well, and one gold mine is already in production some fifty miles beyond Springs, while two more are in the process of development.

THE WEST WITS LINE.

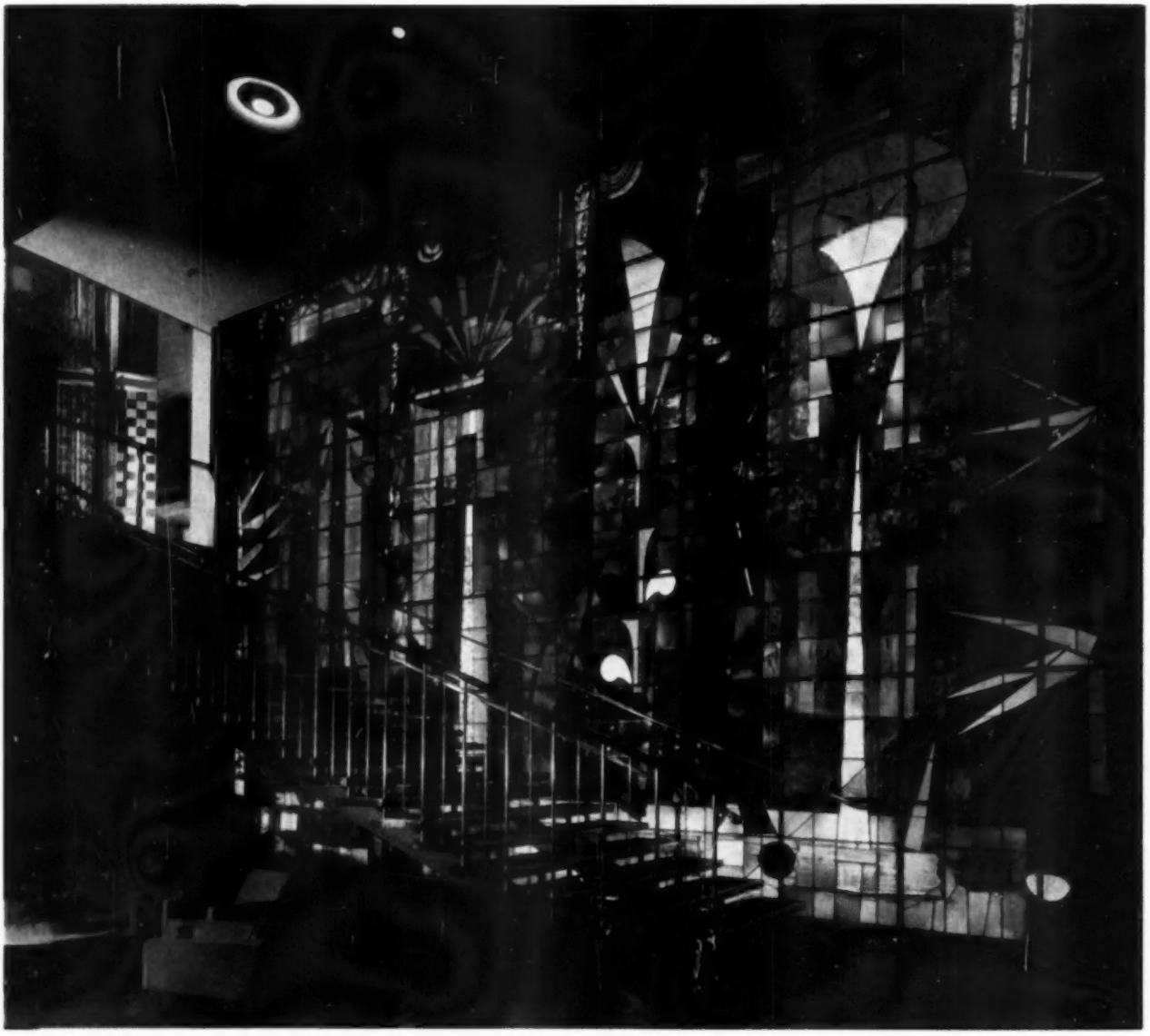
The first two mines to be established on the West Wits Line were at Venterspost and Libanon, not far from Randfontein. A much richer property (Blyvooruitzicht Gold Mining Company Ltd.) was then opened up further to the West. The gold values there were found to occur in a carbonaceous reef known as the 'Carbon Leader', which proved later to contain uranium as well. This reef exists in the mines of the Central Witwatersrand but does not contain enough gold or uranium to be payable. At Blyvooruitzicht it turned out to be so rich that for many years the mine was by far the wealthiest in South Africa, regularly producing gold to the value of nearly £750 000 per month and subsequently furnishing its quota of uranium.

In 1945 work was started to open up two mines adjoining Blyvooruitzicht—West Driefontein and Doornfontein—both containing the Carbon Leader. Of these, the former has surpassed Blyvooruitzicht in gold production and is now making a profit of about £1 000 000 per month. It is served by five surface shafts, the last of which (No. 5) is equipped with the large four-rope friction winding engine that is the subject of this article. The only other multi-rope friction hoist of comparable size in the world—except perhaps in the U.S.S.R.—is at Stillfontein in the Klerksdorp Gold-field. It is similar in design to that at West Driefontein and the mechanical parts were supplied by G.E.C., but it does not wind from so great a depth.

DEVELOPMENT OF WEST DRIEFONTEIN MINE.

The development of West Driefontein Gold Mining Company Ltd. began in 1945 with the sinking of No. 1 and No. 2 Shafts. Shortly afterwards No. 3 and No. 4 Shafts were started, being required to open up the mine for normal working. Designs were also put in hand for a treatment plant for the production of gold; a uranium section was added later. Subsequently, the existence of the Carbon Leader was proved at the western end of the property, where a gold-bearing reef, known as the Ventersdorp Contact Reef, was also found to occur. No. 5 shaft was therefore planned to enable these reefs to be worked.

The mine went into production in 1952. No. 5 Shaft started hoisting ore in 1959, and the tonnage now being sent to the treatment plant (130 000 tons per month) is nearly double the initial output of the mine. Further extensions are in hand, including additional crushing capacity for ore from the Ventersdorp Contact Reef, and by 1964 the total output of the mine is expected to reach 200 000 tons per month. The Main Reef, from which millions of pounds worth of gold have been extracted in the Central Witwatersrand, has also been located in the area of No. 5 Shaft. It seems likely, therefore, that the ultimate total production from the mine will be considerably in excess of the 200 000 tons per month envisaged at present.



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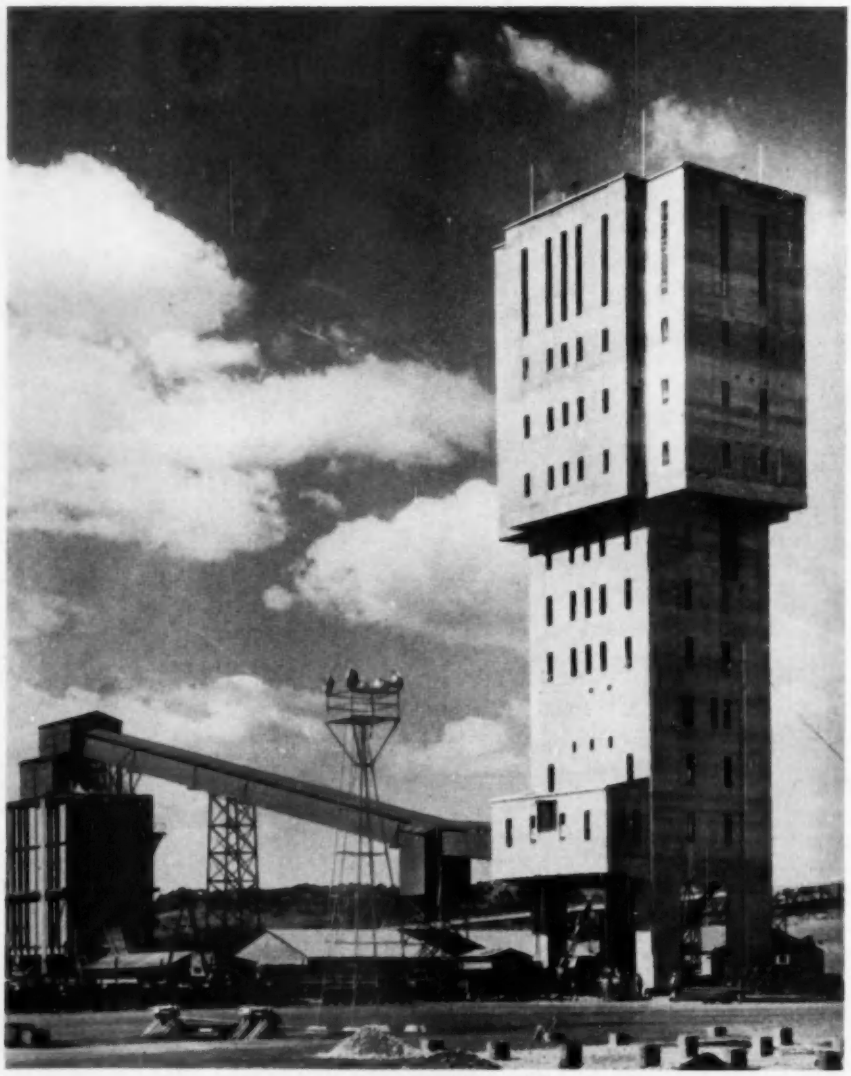

Fig. 1.—Concrete tower of No. 5. shaft.

No. 5 SHAFT.

No. 5 Shaft is circular in shape with a diameter of 25 ft and is divided into six compartments accommodating the conveyances of three separate winders. The underground development of the area served by the shaft has been planned for the ultimate production of 180 000 tons per month mined from all three reefs, the ore being brought to a central loading station located at a depth of 5460 ft below ground level. It was decided that these conditions called for the provision of a single high-capacity multi-rope friction winder for hoisting the ore. Accordingly an order was placed with G.E.C. for a four-rope winding engine of this type, powered by two d.c. motors of 2050 h.p. each. The ore is raised in two balanced bottom-discharge skips with a capacity of 15 tons each at a speed of 3000 ft/min. The maximum capacity of the winder is 370 short tons per hour and provision for automatic operation has been included. The mechanical parts were designed at the Company's Erith Works and manufactured locally by the Vanderbijl Engineering Corporation. The electrical equipment was designed and manufactured at the Company's Witton Works.

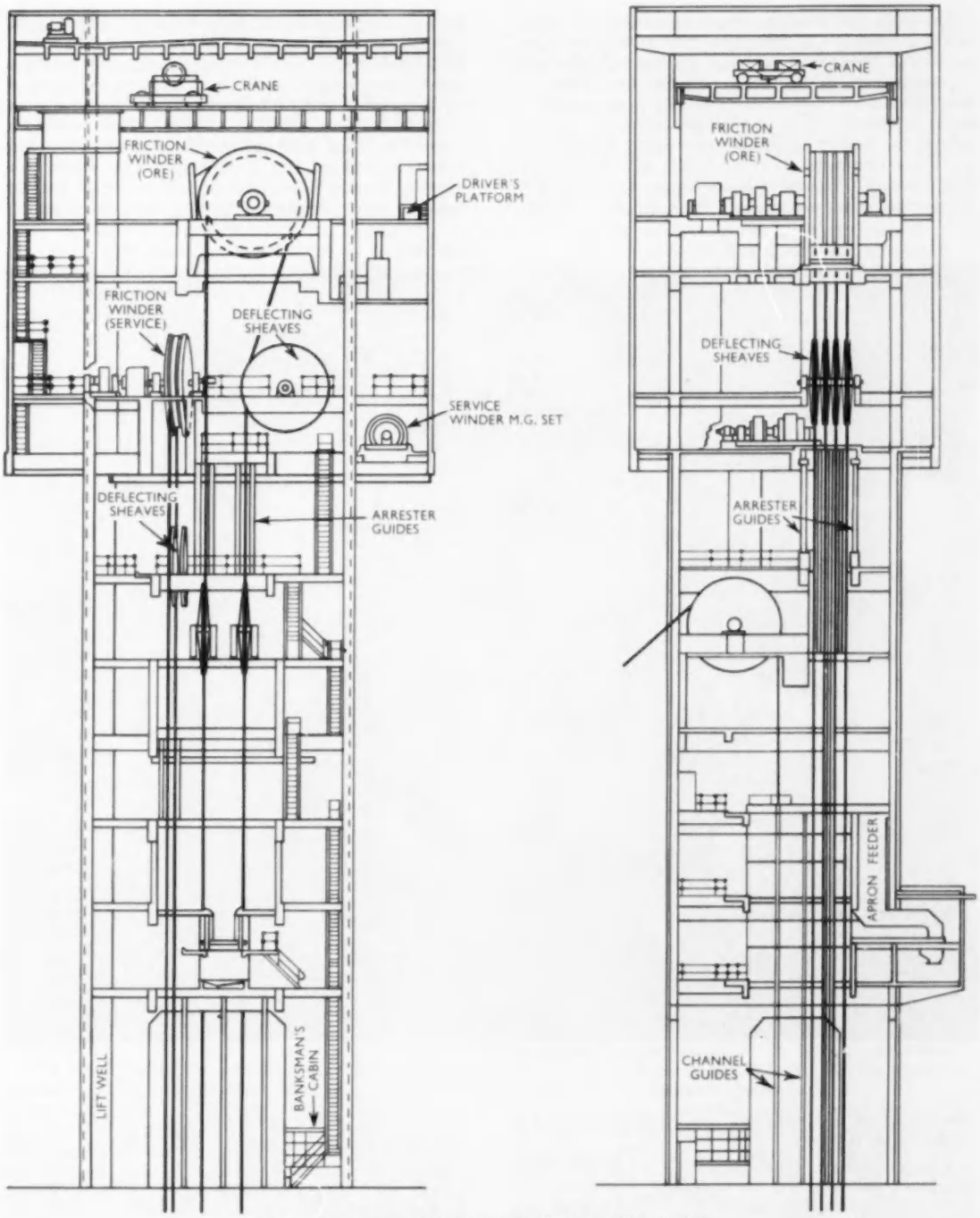

Fig. 2.—Arrangement of the winders in the tower of No. 5. shaft.

The other two winders, which were not supplied by G.E.C., comprise a twin-rope service friction hoist handling a three-deck cage and a counterweight, and a conventional double-drum winder for men and materials sited at ground level remote from the head-frame structure. The two friction hoists and the sheaves for the double-drum winder are mounted in a concrete tower with an overall height of 213½ ft, built over the shaft. The exterior is illustrated in fig. 1 and the internal arrangement is shown in fig. 2.

3000 ft, and it was therefore realized that problems might be encountered with winding depths of 5500 ft, particularly with regard to equalization of the tensions in the four winding ropes. For this reason the drum of the West Driefontein winder (fig. 3) was designed as an extremely rigid, fabricated, mild steel structure secured by fitted bolts and welding to two cast-steel bosses keyed on the drumshaft. The drum was manufactured in halves for ease of transport and to facilitate raising it into the tower structure. Even so,

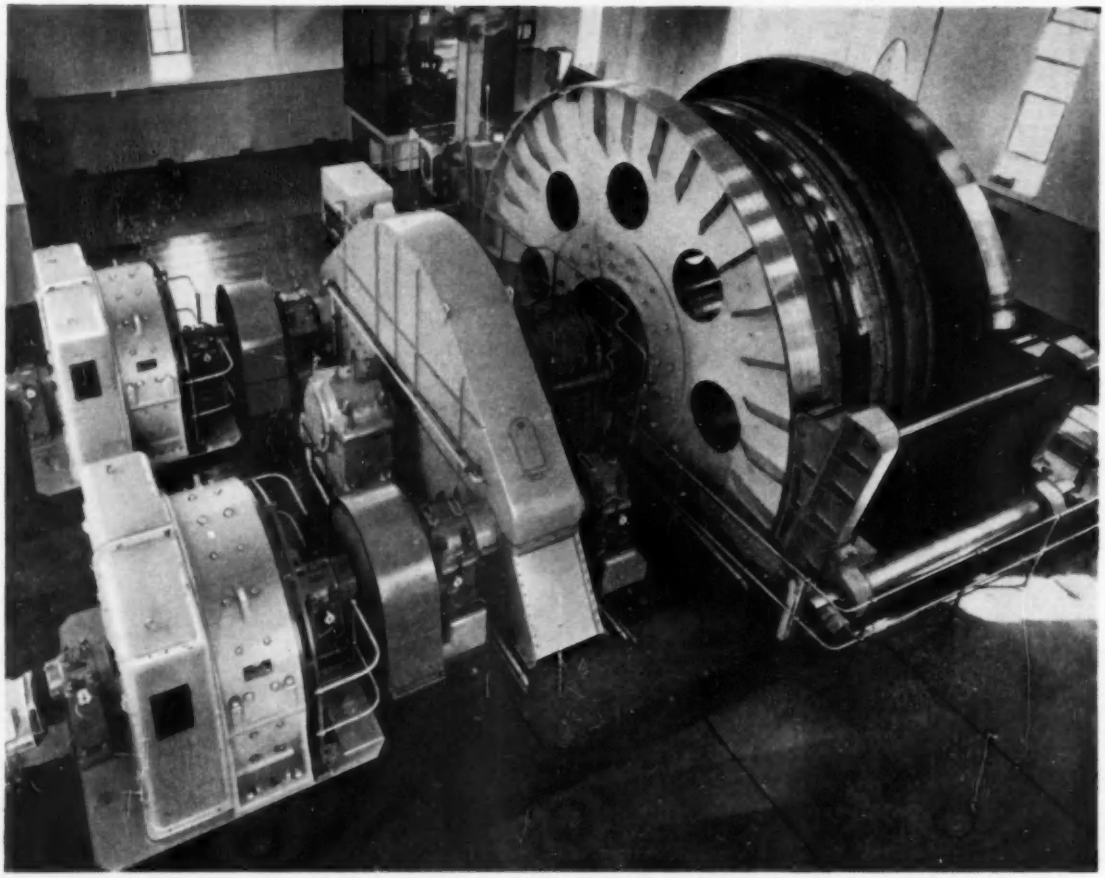

Fig. 3.—4100 h.p. friction winder for No. 5. shaft.

MECHANICAL EQUIPMENT OF THE FOUR-ROPE FRICTION WINDER.

The principles of multi-rope friction winding were, of course, pioneered on the continent of Europe, but at the time the contract for the No. 5 shaft winder was placed, the only installation of comparable size was that at Hannover Colliery in Germany. This equipment, however, operates from a depth of only about

each half had a net weight of 30 tons. The two halves were secured on erection by fitted bolts and shrink rings round the central bosses.

The diameter of the drum at the rope centres is 17 ft 6 in. and the four 1·75 in. diameter ropes are spaced at 24 in. pitch. One brake path, 20 ft in diameter, is incorporated on each end of the drum. The rope tread material, of dovetail section, is held in

position by wedge-shaped timber baulks securely bolted to the drumshell. The rim of the drum is also arranged to accommodate division plates, which allow two ropes to be coiled on the drumshells simultaneously and thereby permit rope installation or changing to be carried out without the need for a special winch.

The main drumshaft is manufactured from forged steel and is in two sections, the principal section supporting the drum and a smaller stub shaft supporting the main gearwheel. The two sections are connected by a solid flanged marine-type coupling and are carried in three self-aligning whitemetal-lined bearings arranged for lubrication by twin oil rings and/or a separate flood system.

As the tower structure is of reinforced concrete it was considered that no elaborate method of accommodating mal-alignment between drum and gear-

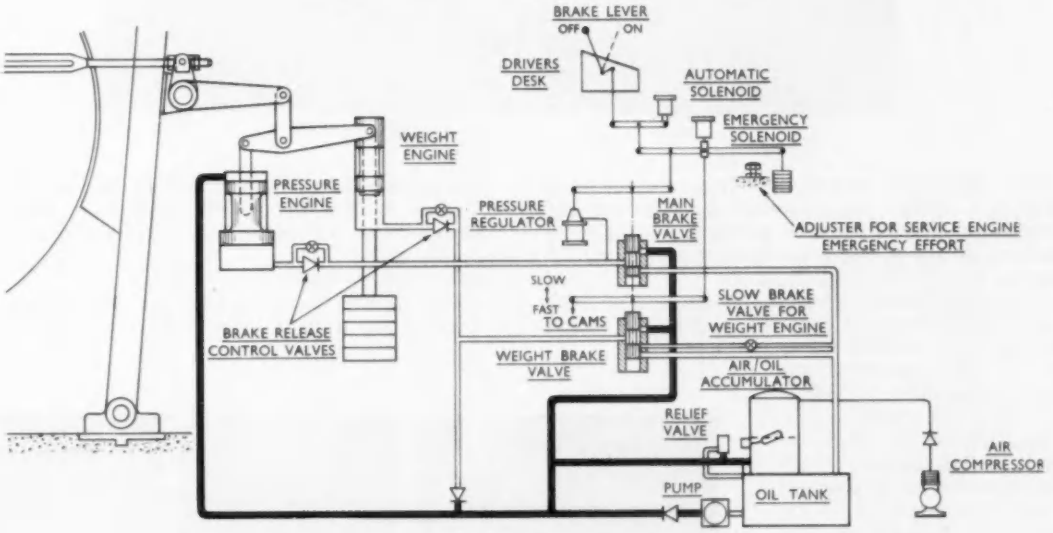

Fig. 4.—Diagrammatic arrangement of brake system.

shafts was necessary. The outer drum bearing was, however, arranged on a soleplate incorporating an adjustable wedge which allows the bearing centre height to be varied, thus providing a means of distributing the shaft loading proportionately between the three bearings.

The single-reduction double-helical gears, which transmit the drive to the drum from the two motors, comprise a fabricated solid-type wheel pressed on to the stub shaft and secured by double tangential keys, and twin forged-alloy-steel pinions integral with their shafts. The gears are lubricated by spray nozzles fed from a separate self-contained oil system. The motor and pinion shafts are connected by Wellman Bibby type couplings.

The mechanical brakes consist of two pairs of straight posts supported on cast-steel anchor brackets firmly secured to the tower structure. To each post is bolted a curved brake shoe lined at a machined face with woven asbestos friction material. The two pairs of posts are operated, through rods and levers, by one of two brake engines.

A hydraulic pressure brake engine is used to apply the brakes under normal manual and emergency conditions, and also when the winder is operating automatically. In the event of failure of the hydraulic system a standard weight engine applies the brakes. Both engines are connected to a common floating lever which applies the brakes, and the mechanics of this lever are such that the maximum braking force exerted is limited to that force exerted by the most powerful engine. Under no circumstances can the braking force of the two engines be transmitted to the shoes. This is of particular importance on a friction winder as such a force could cause slip of the ropes over the drum due to the excessive retardation.

The pressure brake engine consists of a two-diameter cylinder fitted with a two-diameter piston and the general principles of operation have previously been described in this journal*. In the present instance the operating pressure is 130 lb/in^2 and the schematic of the hydraulic circuit is shown in fig. 4.

The auxiliary equipment supplied with the winder includes a twin-vertical-screw depth indicator, with magnifying dials for the final two revolutions of the drum, and a Black speed controller for detecting overspeed or overwind conditions. This equipment, together with the geared potentiometer which controls electrically the speed of the winder relative to its position in the shaft, is driven from the

* *G.E.C. Journal*, Vol. 26, No. 3, p. 120, Summer 1959.

Fig. 5.—3800 h.p. Ward Leonard M.G. set.

winder drumshaft through rope-creep compensating devices. These devices correct automatically the relative positions of the skips and drum, as the ropes are not, of course, rigidly anchored to the drum, and tend to creep over it when in service.

Deflecting sheaves, 15 ft in diameter and of fabricated construction, are provided to adjust the centres of the four winding ropes to suit the centres of the skips in the shaft. The four sheaves were designed and manufactured in halves for ease of installation. They are mounted on a common shaft, one outer sheave being keyed and the remainder free to rotate individually to accommodate any relative variations in travel between ropes during winding. The ends of the shaft are carried in roller bearings and grease lubrication both for the bearings and the bushed rotating sheaves is incorporated. The sheave rims are recessed to receive split rope-tread inserts of dovetail cross-section.

ELECTRICAL EQUIPMENT.

Motors.

The winder is driven by two 2050 h.p. 500 rev/min 0/700 volt d.c. motors. These are enclosed at the commutator ends and are arranged for forced-draught cooling by two 38 in. diameter Aerofoil fans. Access doors are provided in the end covers for maintenance and inspection.

Motor Generator Set.

The variable voltage supply for controlling the speeds of the motors is derived from a motor generator

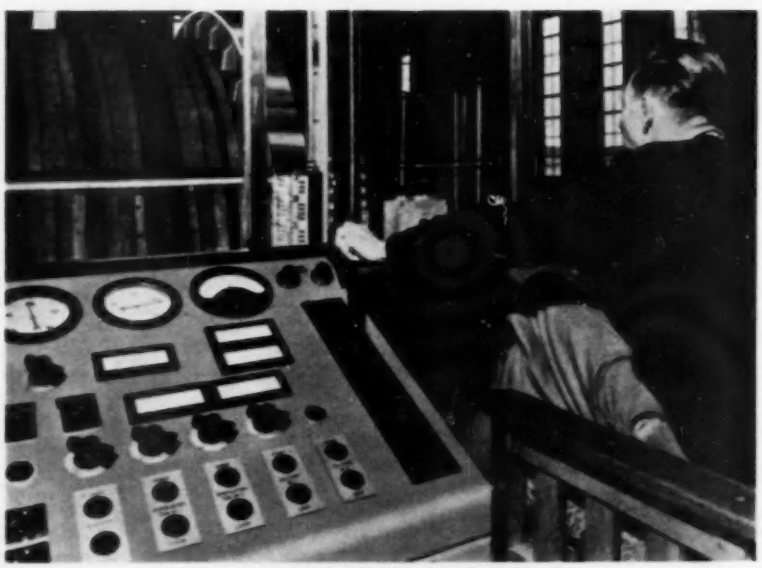

Fig. 6.—Control desk for No. 5 shaft winder.

set operating on the Ward Leonard principle. The set comprises two 1600 kW generators and a 3800 h.p. 735 rev/min induction motor mounted on a common bedplate (fig. 5). The motor is started by a liquid starter and is fitted with rotor short-circuiting gear.

The motor generator set is housed at ground level some distance from the base of the winder tower, and the route length of interconnexions between the winder motors and generators is approximately 500 ft. To reduce cable costs to a minimum, a system of connecting motors and generators in series in the sequence generator-generator-motor-motor was adopted in place of the more usual generator-motor-generator-motor sequence. This permitted two runs of four single-core 1·0 in² cables instead of four.

unbalance relay with additional instantaneous protection against short-circuit faults.

Control Exciter Scheme.

Excitation for the main generator fields and a constant voltage d.c. supply for auxiliary equipment is provided by a four-machine exciter set. The field excitation is provided by two multi-field exciters of laminated construction, connected in cascade. Fig. 7 shows the basic scheme in simplified form.

Fields *A*1 and *A*2 are the pattern fields and their strength and direction are determined by the pattern speed signal circuit which is either manually or automatically controlled. A fraction of the voltage of one motor supplies the main reset fields *E*1 and *E*2, this

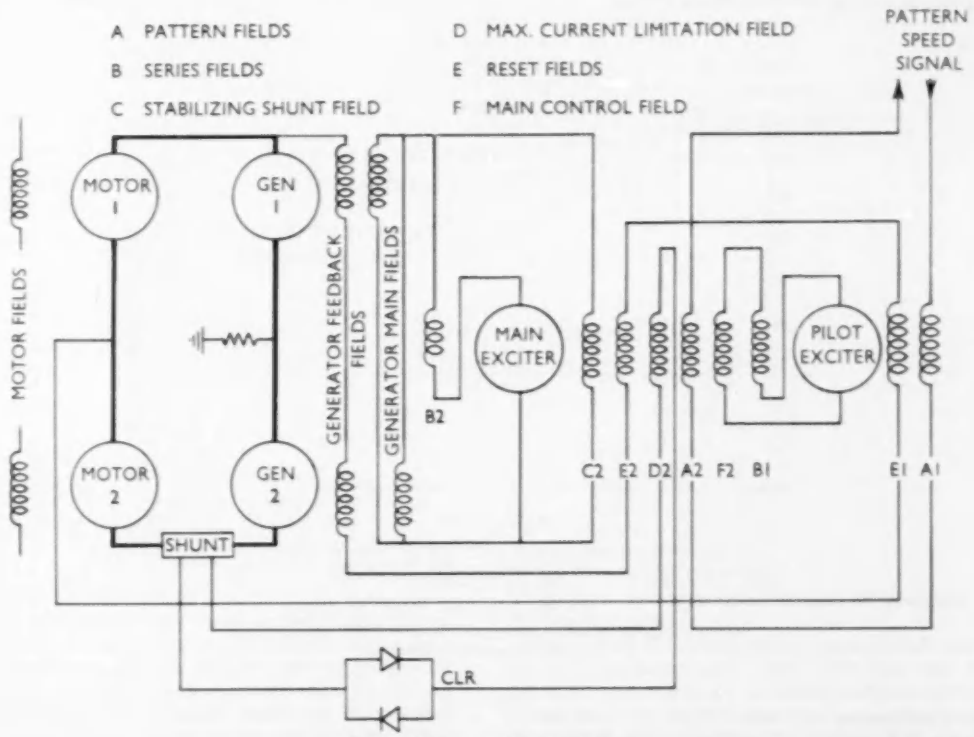

Fig. 7.—Basic control exciter circuit.

To avoid overvoltages on the main d.c. loop due to an earth fault on a machine or cable, the interconnexion between the generators is earthed through a resistor. Any significant current flowing in the resistor due to an earth fault is detected by a relay which trips the winder safety circuit and thus removes the excitation.

The 6·6 kV supply to the stator of the M.G. set driving motor is controlled by a solenoid-operated oil circuit breaker rated at 400 amp at 150 MVA and protected by a thermal pattern overload and phase

voltage being related to the motor speed. *E*1 and *E*2 oppose *A*1 and *A*2 giving a balance when the motor reaches a speed as called for by the pattern speed signal circuit.

Feedback fields, connected in the *E*1 and *E*2 field circuit, are provided on the main generators to prevent an overshoot in speed before reaching a steady condition. Field *A*2 opposes the main controlling field *F*2 and is so proportioned that, after the pilot exciter saturates, the net effect of *F*2—*A*2 is constant. Therefore, when the difference between the required speed

and actual speed is less than 10%, the rate of correction of the error is proportional to the magnitude of the error, but when the difference is greater than 10%, the rate of correction remains constant.

Maximum current limitation field *D2* is fed from a shunt in the main d.c. loop and opposes the main controlling field *F2*. The non-linear resistance characteristic of a rectifier CLR in series with *D2* serves to give a stable and predetermined value to the maximum current obtainable.

Maximum power limitation (when accelerating up to full speed) is obtained by using the output of a tacho-generator driven from a winder motor to boost field *D2* and thus depress the maximum current. This feature provides graded acceleration of the winder even though the driver's power lever is kept fully over in the full-speed position during the accelerating period.

of wind, so geared to the winder friction wheel shaft that the contact arm of one makes nearly a complete revolution per wind, while the other makes a complete revolution for about 550 ft of travel of the skip.

This provides, in effect, a long-range cam gear unit without the disadvantages of mechanical linkages, and for which the 'profile' can be accurately predetermined. Minor changes to profile can be made by adjustment of the resistance steps and major changes by reconnexion of the contact studs. Fig. 8 shows the determination of the resistance grading for this winder with constant deceleration over the last 400 ft of wind.

The output velocity/distance curve shows the actual characteristic required of the winder, the input velocity/distance curve has the same characteristic but is biased to allow for the response time delay of the electrical circuit (in this case 2 seconds). Super-

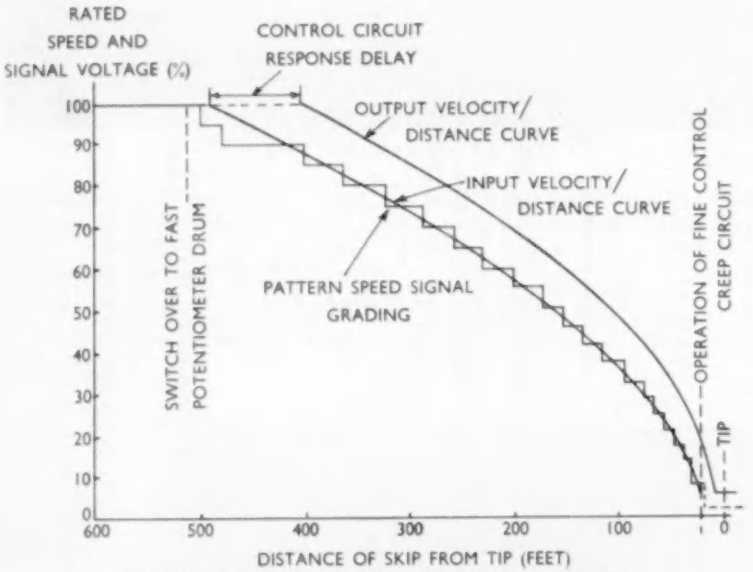

Fig. 8.—Velocity/distance curves and pattern speed signal voltage grading for automatic winding.

The combination of series field *B2* and shunt stabilizing field *C2* (in opposition to *B2*) is used to dampen response following change in the reference quantity, and to increase the sensitivity of the system to small changes in *F2*. *B2* is slightly predominant over *C2* but is slower to respond to change of condition due to the inductance of the main generator fields.

SPEED CONTROL CIRCUIT.

During manual winding, the pattern speed signal is derived from the rectified output of an induction regulator controlled directly from the driver's power lever. For automatic winding, the signal is derived from a geared potentiometer device (fig. 10). This comprises two potentiometer drums for each direction

imposed on the input curve are shown the pattern speed signal voltage steps to give the required input characteristic.

The 'slow' potentiometer drum provides a full speed signal from initiation of the wind until the skip reaches a point some 500 ft. from the tip. At this point, the contacts are arranged to switch the control signal to the 'fast' potentiometer drum. This drum provides a decreasing signal in accordance with the predetermined voltage/distance characteristic and the winder decelerates to creeping speed a short distance from the tip. A magnetic switch operated by the skip then switches in the fine control circuit, which adjusts the creep speed by comparing the output of a tacho-generator against a pre-set voltage and altering the

speed signal accordingly. A limit switch at the tip causes the brakes to be applied automatically.

During manual winding, the pattern speed signal output from the geared potentiometer is used to give supervisory control of the driver's power lever. This output is continuously compared in a monitoring relay with the output from the manual control induction regulator. If the pattern speed signal output drops below the induction regulator output, for example if the driver fails to operate his power lever towards a lower speed when the deceleration period should commence, a torque motor driving through a magnetic clutch pulls the driver's lever over until creep speed is reached. In an emergency, this feature can be defeated by a special pedal switch.

a cam in the auxiliary drive and the other by the skip in the shaft; the direction of rotation is fixed by the first switch to open. Thus, the position of the skip in the shaft as indicated by the depth indicator, etc., is always maintained within a certain margin either side of the true skip position. By using this system it is not necessary for the winder to remain stationary while compensation is taking place, thus avoiding interference with the winding cycle.

ERECTION AND COMMISSIONING.

Erection of the hoist followed conventional procedure, except that it was carried out some 200 ft above ground level. To ensure perfectly true running of all rotating parts it was considered desirable that the

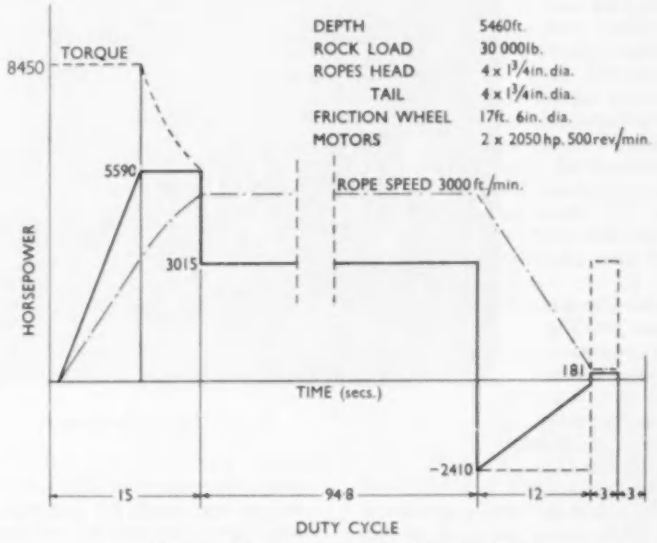

Fig. 9.—Duty cycle for No. 5 shaft friction winder.

ROPE-CREEP COMPENSATION.

To compensate for rope-creep on the friction drum, the auxiliary drives to the depth indicator and geared potentiometer and to the Blacks hoist controller are adjusted at the end of each alternate wind by the use of a special gearbox. This is similar in layout to a motor car differential gearbox, where the two half-axles can be considered as forming the input and output shafts respectively and the crown and pinion wheels are represented by a worm wheel and worm.

The output shaft normally runs at the same speed as, but in the opposite direction to, the input shaft. If the worm wheel is rotated a certain amount by a geared motor, however, the output shaft is moved relative to the input shaft, thus giving the necessary relative adjustment between the friction wheel and the depth indicator, etc., even while the winder is in operation.

The geared motor is arranged to run for a fixed time at the end of each wind and the direction of rotation is governed by two switches. One of these is operated by

brake paths and rope treads should be machined with the hoist in position.

For trueing the brake paths a special slide rest and rig were manufactured. The slide rest was hand-operated and traversed a carbide-tipped lathe tool across the width of each brake path. Light cuts were taken until a continuous true surface was obtained. The drum was rotated by the main motors during this operation and credit is due to the form of electrical control provided in that the drum speed had to be maintained steady for long periods at speeds of less than about 3 rev/min., i.e., about 5% of full speed. The rope treads were trued by means of a portable motor-driven grinding rig fitted with a coarse-grit wheel profiled to the true shape of the tread. The grinder was run at a relatively slow speed to avoid burning the rubber.

The rope treads for the deflecting sheaves were also trued by means of the same grinding rig, but for this duty the hoisting ropes were in position, and the

sheaves were driven by them while the hoist was run at slow speed.

As had been anticipated when the hoist was designed, operating depths of 4000 ft and over brought to light problems not previously encountered. The hoist at Stillfontein was the first four-rope friction winder to be put into commission in South Africa and it was found very soon after commissioning that considerable wear of the rope tread material was being experienced. Extensive investigations followed and even now a full solution to the problem has not been evolved. It has been found, however, that Non-spin ropes (instead of the conventional Langs Lay ropes) operating on hard rubber inserts, give a reasonably satisfactory wear factor. As a result the No. 5 shaft hoist at West Driefontein has now been put into commission with Non-spin ropes and rubber inserts.

While it is possible to install the winding and balance ropes using the hoist itself as a prime mover, it was considered expeditious in this instance to employ a separate winch. The winch had previously been in operation as a platform hoist during shaft sinking operations and was of the double-drum type mounted at ground level.

The balance ropes were the first to be let down the shaft and this operation was fairly straightforward. The two ropes were wound from the reel on which they were supplied by the rope manufacturer, one on to each drum of the winch. The free ends of the two ropes were fastened next to a suitable cross head and lowered down the shaft. Once in their approximate working position the ropes were clamped at the bank and shaft stations and disconnected from the winch.

Two winding ropes of opposite lay were next wound onto the winch. By means of pilot ropes they were then led up the tower and over the deflecting sheaves and main winder drum. The main winder and the winch were next rotated in unison until the main rope ends were at the bank position. Here they were clamped to No. 1 skip. This skip was then lowered to shaft bottom, the winder and winch still being rotated to maintain the same rope speed.

One of the balance ropes, already in the shaft, was attached to the No. 1 skip at the shaft bottom and the other end of the same rope to the No. 2 skip, still on the surface. Using the main winder only, the No. 1 skip was brought to the surface. The remaining two main winding ropes were coiled on the winch drums and led up over the deflecting sheaves and main winder drum and clamped to No. 1 skip. No. 1 skip was then lowered to shaft bottom while the winch and main winder once more maintained the same rope speed.

All main winding ropes and the other balance rope were connected to their respective conveyances and the system was ready for operation. For changing the winding ropes a similar procedure will be adopted, the two ropes being handled simultaneously. The No. 1 and 2 skips will, however, probably be baulked at shaft bottom and top respectively.

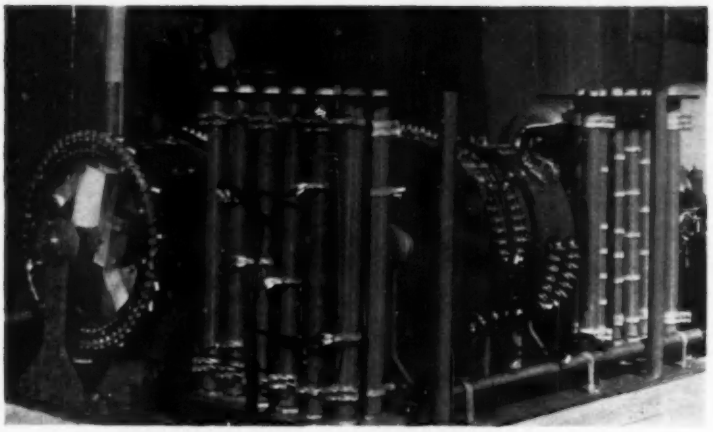

Fig 10. Geared Potentiometer.

ACKNOWLEDGEMENT.

Acknowledgement is due to the Gold Fields of South Africa Ltd. for providing the background information for this article and for permission to publish the photographs reproduced therein.

CORRECTION

We regret that the name of one of the two authors of ' Water Cooling of Power Cables ', appearing in the Summer 1960 issue of the *G.E.C. Journal*, was incorrectly given as D. A. Thomas and should have been D. A. Thoms, B.SC.(Eng.), A.M.I.E.E., of the Central Electricity Generating Board. We apologize to Mr. Thoms for any inconvenience and misunderstanding this error may have caused.

Automatic Control of large Turbo-Generators

By F. L. TOMBS, A.M.I.E.E. and H. E. GARDAM, A.M.I.Mech.E., M.I.Mar.E., A.M.R.I.N.A.,
Power Plant Division, Engineering Group.

INTRODUCTION.

TO generate electricity cheaply it is necessary to install the largest practicable turbo-generators employing high steam pressures and temperatures, and in recent years the unit size and steam conditions of generating station plant have been increasing throughout the world. For example, the Central Electricity Generating Board are installing 550 MW cross-compound sets at Thorpe Marsh, 500 MW tandem-compound sets at West Burton and 375 MW supercritical sets at Drakelow C. A section through a modern 200 MW reheat turbo-generator manufactured by G.E.C. is show in fig. 1. The operating conditions of these large sets must be carefully controlled at all times if the maximum economic benefit and highest availability are to be obtained, especially on two-shift operation.

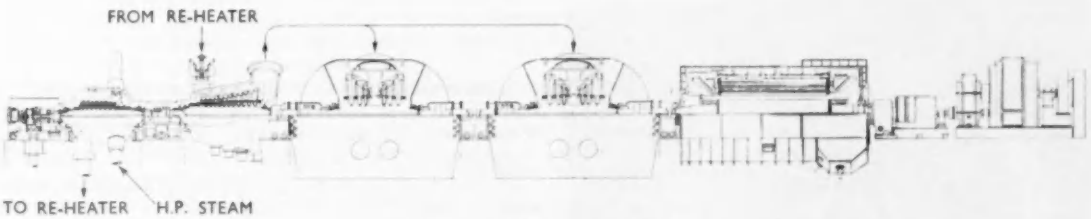

Fig. 1.—200 MW turbo-generator.

Automatic combustion control of large boilers has been practised for many years and has fully justified itself by reducing the fuel consumption and the strain on operators, and by increasing plant availability and efficiency. Modern turbo-generators are fully protected when on load, but in the past the safety of the plant during starting, loading, and shutting down has been left to the operator's judgement. The increased care needed when operating large sets with advanced steam conditions, combined with the need for rapid starting on two-shift operation, make it desirable to introduce integrated automatic control of the turbo-generator and its associated condensing and feed-heating plant.

ADVANTAGES.

The advantages of automatic turbo-generator control include:

(*a*) Consistent operation in accordance with the techniques established by the manufacturer in comprehensive tests designed to achieve the fastest permissible operation.

(*b*) More rapid starting and loading because the rate is no longer dependent on the individual operator's experience and the plant is protected by built-in safety controls. This is particularly important on two-shift operation.

(*c*) Automatic shut-down in the event of a fault enables the operator to check the cause more rapidly.

(*d*) Increased reliability because the stresses are limited to those determined during the starting trials upon which the automatic control is based.

(*e*) A simple control desk with the minimum of switches and controls.

(*f*) Protection of the whole plant against mal-operation. The control checks the positions of the required valves and corrects wrong settings, starts and stops auxiliary pumps, operates the valves in the correct sequence, and generally ensures that no routine operation is omitted.

(*g*) Economy. Pending experience of the automatic control of large turbo-generators it is difficult to calculate resultant savings with accuracy. However, it is anticipated that the capitalized savings

due to the time saved and increased reliability will outweigh the initial capital investment, as it has done in many industries. The capital cost of automation is largely independent of the unit size and thus its application to large units should enhance the gains resulting from their use.

To gain the utmost benefit from automation a very detailed knowledge of the plant's operating capabilities is required and G.E.C. has and is giving special attention to the rapid starting and loading of turbo-generators. Some early results have been described in the article 'Controlled Starting Tests on 60 MW Turbo-Alternators'.* More extensive trials are being carried out on the controlled starting of reheat machines.

SEMI-AUTOMATIC CONTROL.

In 1959 The South of Scotland Electricity Board instructed G.E.C. to design a control system for their 200 MW turbo-generator sets being installed at Kincardine Generating Station and when the first of these is commissioned in 1962 it will have one of the most advanced automatic control systems.

Cold starts rarely occur and require a prolonged starting routine, whereas hot starts occur daily on shift operation when rapid operation is possible. Therefore the paramount requirement is the safe starting, loading and shutting-down of sets on shift operation and the semi-automatic control for Kincardine has been designed specifically to do this.

The operation of the turbine, alternator, feed and circulating water systems, and their associated plant is divided into a starting sequence of 6 groups, a loading sequence of 4 groups, and a shutting-down sequence of 3 groups. The operations and completion checks comprising a typical group are shown in Table 1. The operations are performed in turn and the sequence cannot proceed unless the completion checks are satisfactory.

The sequences and groups are initiated from the unit control room by means of the simplest controls, which consists of:

(1) A sequence selection switch with four positions, 'load', 'start', 'hand', 'shut-down'.
(2) A single group-initiating pushbutton.
(3) An indicating lamp fascia displaying the progress of the operations and the state of the plant at any time.
(4) Four loading-rate adjusting dials.
(5) A load-setting dial.

The controls are fully interlocked and protected so that mal-operation of the plant cannot occur on automatic control however the sequence selection switch and the group initiating pushbutton are operated.

The availability of the machine is guarded against failure of the automatic equipment in two ways. The set can be switched to manual control at any time, and

* *G.E.C. Journal*, Vol 26, No. 4, 1959.

TABLE 1.

START TURBINE.

Operation Number	Description	Motivation	Completion Check
5/1	Reset main oil release valves, providing vacuum is above 24 in. Hg.	When vacuum P/S No. 18 is closed, energize solenoid No. 3.	Primary tripping circuit oil pressure switch No. 11.
5/2	Make continuation of sequence dependent on relay oil pressure.	Energize relay.	Relay contact.
5/3	Check that supervisory gear is running.	Start motor.	Contact of relay on h.f. output.
5/4	Start turbine by operating starting handwheel 0V70.	Start slow-speed motor to open.	Aux. switch on barring gear.
5/5	Shut starting handwheel 0V70.	Start high-speed motor to close.	Fully closed limit switch.
5/6	Increase turbine speed to 500 rev/min and maintain speed at 500 rev/min. 0V70 alarm to stop increase of speed whenever supervisory gear reads high.	Control motor.	Speed increase will be programmed by speed controller which will signal completion to sequence controller.
5/7	Stop jacking and barring oil pumps.	Stop motors.	Aux. switches on motor starter.
5/8	Shut quick-start ejector air suction valve *ASV*1.	Start motor to close.	Fully closed limit switch.
5/9	Shut quick-start ejector steam supply valve *SV*5.	Start motor to close.	Fully closed limit switch.

when on automatic control a check circuit bypass switch enables the operator to defeat any completion check fault when he is satisfied with the state of the machinery. An automatic record is kept of whenever this bypass switch is used.

The auto-control can be operated in a number of ways. Normally the switch is turned to ' start ' and the group-initiating button pressed, whereupon the operations comprising group 1 are automatically performed and indicated on the lamp fascia. Subsequently the button is pressed on completion of each group at a time convenient to the operator controlling the boiler plant, until the starting sequence has prepared the set for synchronizing.

After the set has been synchronized and loaded manually to 10 MW the loading rates and load required are set on dials and the sequence selection switch is turned to load. Subsequent operations of the group-initiating button automatically load the machine at the set rates in four stages of 10 to 30, 30 to 60, 60 to 120 and 120 to 200 MW, up to the set load. The load can be increased automatically to any intermediate load by turning the load-setting dial and pressing the group initiating button as necessary.

Whenever the machine is on auto-start or load, the turbine supervisory gear and other important measurements, such as the steam/casing temperature differentials, are continuously monitored and should safe limits be exceeded an alarm is sounded. The acceleration or loading of the machine is then automatically suspended until the readings are again satisfactory, when acceleration or loading is automatically resumed. Such occasions are unlikely to occur because the acceleration and loading rates built into the controls are the safest and yet fastest possible.

When a conventionally controlled turbo-generator trips for any reason, the operator has to exercise his judgement and carry out a number of operations. Under G.E.C. automatic control, if a set trips at any time during starting, loading, or when on load, the subsequent loss of turbine relay-oil-pressure initiates the shutting-down sequence to take the machine safely and progressively to the barring state. The appropriate valves are opened and closed and all the necessary pumps started and stopped as required. The whole plant is therefore additionally safeguarded against mal-operation and the operator, freed from the routine work of controlling the set while running-down, is able immediately to investigate the cause.

Normal shutting-down is achieved by turning the sequence selection switch to ' shut-down ' and operating the group-initiating button on the completion of each preceding group in a manner similar to that used when starting and loading.

If desired, the auto-control can be switched to:

(1) ' Load ' following a manual start.
(2) ' Shut-down ' from hand control.
(3) ' Shut-down ' during auto-starting and loading.

CONSTRUCTION.

The G.E.C. automatic control employs well-proved simple mechanical and electrical components customarily fitted in modern generating stations. This particular semi-automatic control is designed only for hot starting on shift operation, which is the major need. The principles employed and equipment chosen readily enable the control system to be extended to the starting and loading of turbo-generators from cold. Further work is proceeding in conjunction with boiler and other plant manufacturers to apply these principles to the overall control of a complete boiler-turbine unit.

Sequence Controller.

The sequence selection switch and group-initiating pushbutton operate a sequence controller, shown diagrammatically in fig. 3, consisting of a number of interlocked heavy-duty uniselectors and relays that initiate each operation sequentially and check that it has been successfully completed before proceeding to the next. A typical heavy-duty uniselector is shown in fig. 2.

The sequence controller switches in and out or checks other controllers such as the specially designed speed and load controllers described below.

Speed and Load Controllers.

The turbine starting and speeder drives have been designed to ensure safe performance on both automatic and manual control. Each is driven by two electric motors through epicyclic gearing; in each case one motor operates the handwheel drives at the fast speed normally employed in generating station practice for manual operation, while the other motor drives at a slower speed regulated by the speed and load control-

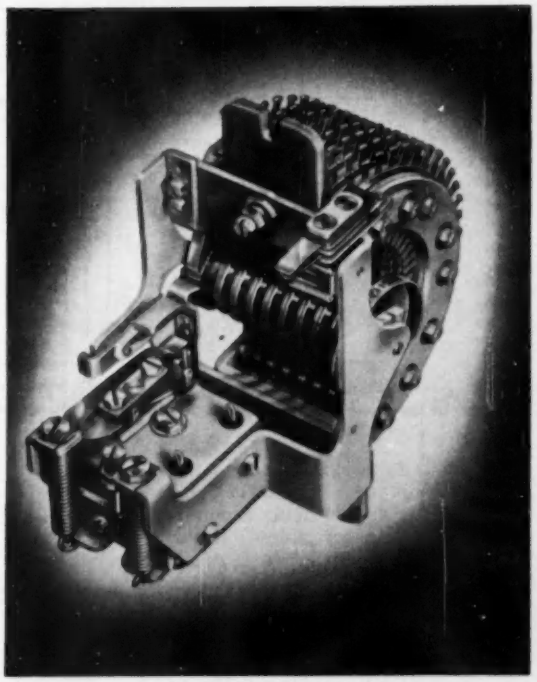

Fig. 2.—Heavy-duty uniselector.

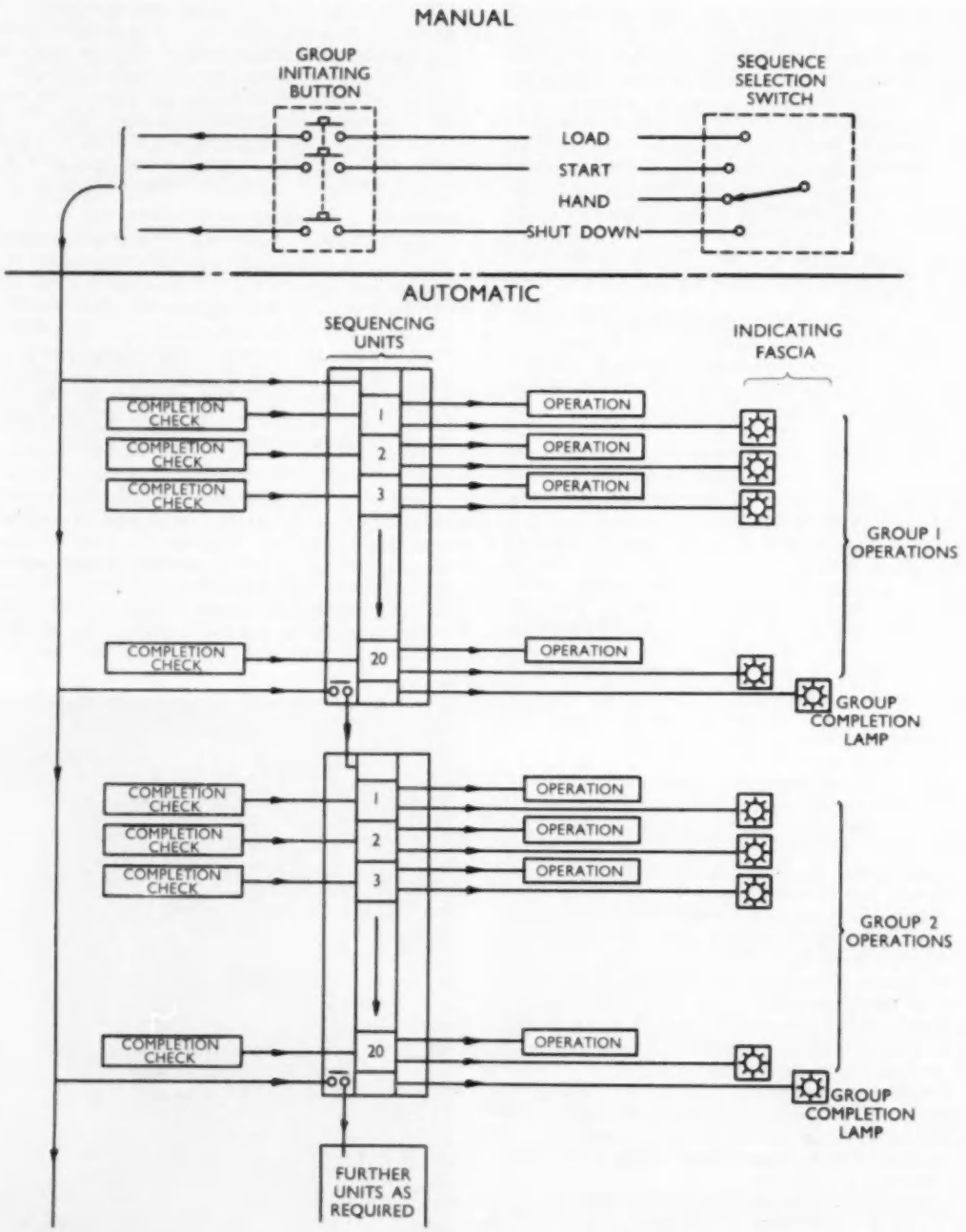

Fig. 3.—Block diagram of sequence controller.

lers. The slower speed drives keep the acceleration and loading rate within safe limits in the event of a control failure.

During starting the speed controller regulates the acceleration and speed continuously by means of the starting handwheel motor, and the load controller regulates the rate of loading and load continuously by means of the speeder handwheel motor. In addition to the supervisory gear lockouts mentioned previously, entirely separate speed and load lockouts are fitted at every stage of increasing speed and load so that three automatic features back each other up to ensure absolutely safe control of the turbo-generator at all times.

The turbine always accelerates from barring to synchronous speed under a predetermined and consistent programme which is adjusted at site to give the fastest safe run-up and is independent of the operators' skill and experience. The machine is loaded at a rate chosen by the operator, but he cannot load the set automatically at a rate greater than the limits adjusted at site and based on carefully controlled tests.

Other Controllers.

These include:

(1) The lubricating-oil temperature controller to maintain the oil temperature constant under all operating conditions. (The sequence controller checks that the oil temperature is acceptable before starting the turbine.)

(2) The dump condenser controls. The sequence controller checks that these have been operated during the starting and shutting-down sequences.

(3) Gland steam controllers. Pressure and temperature controllers automatically maintain the gland steam at the desired values under all operating conditions.

Lamp Fascia.

A typical indicating lamp fascia is shown in fig. 4. The sequence lamps indicate which sequence is energized and the operation lamps are illuminated and extinguished as the sequence controller passes through each operation. The group-completion lamps light and stay alight as each group is completed and are not extinguished until the sequence is changed. Thus the position reached at any moment is shown, and if the sequence controller should stop for any reason the step is indicated by the appropriate operation lamp, which remains alight.

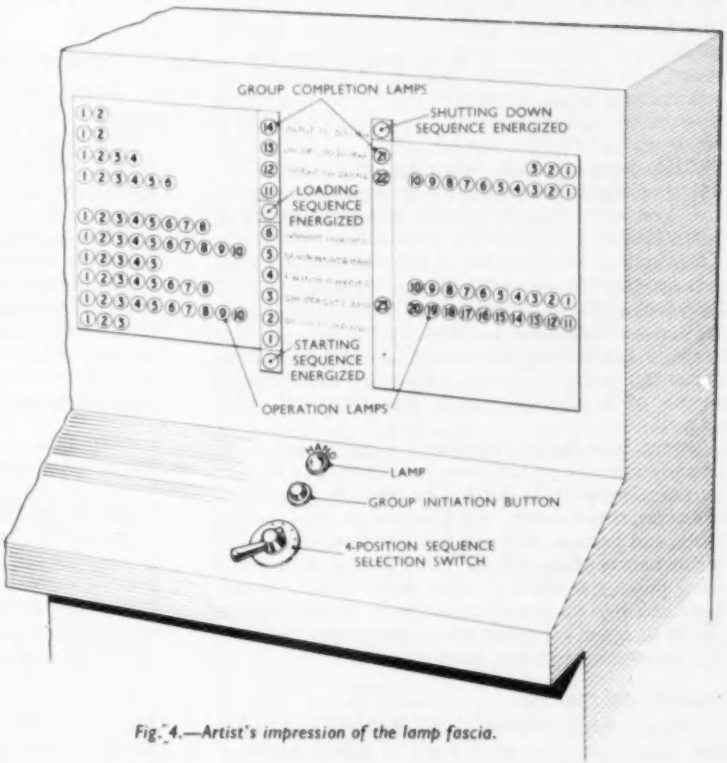

Fig. 4.—Artist's impression of the lamp fascia.

Standby Plant.

All the standby plant starts automatically in the conventional manner on failure of the plant in use.

Acknowledgement.

Acknowledgement is due to the South of Scotland Electricity Board for permission to publish this article and to both them and their consulting engineers, Messrs. Kennedy and Donkin, for much encouragement and assistance in developing this control.

Transistor Inverters for Operating Fluorescent Lamps from d.c. Supplies

By D. DUNTHORNE, B.Sc.(Eng.), Research Laboratories,
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Works, Coventry.

THE inherent high luminous efficiency of the fluorescent lamp makes it an attractive proposition for transport lighting where the source of power is usually a battery of somewhat limited capacity. These systems generally use 24 volt batteries and since it is not possible to operate fluorescent lamps directly from such a voltage, the majority of applications have in the past used low-voltage incandescent lamps. In order to ensure satisfactory operation of the lamp, some form of inverter to convert the d.c. supply into an alternating supply of a suitable voltage and frequency must be used.

In the past, rotary inverters, vibrators, and more recently mercury-jet inverters, have been used for this purpose, but all these systems are basically dynamic in character, that is to say, they have one or more moving parts, and because of this require frequent and skilled maintenance. Recently the development of inverters using power transistors or other semiconductor devices has eliminated all moving components. These inverters can be designed to operate a fluorescent lamp load from d.c. voltages up to a few hundred volts.

CHOICE OF CIRCUIT.

Perhaps the best known transistor inverter circuit is the square-wave circuit[1], shown in rather simplified form in fig. 1. The transistors are used to switch the positive terminal of the battery alternately between the two ends of the primary winding, switching between one transistor and the other taking place when the transformer core saturates. Control of the base current is accomplished by the resistor R_b, which is usually made variable, and resistor R_s ensures reliable starting of the inverter. The circuit has the twin advantages of simplicity and inherently high efficiency and for these reasons it is widely used, either for d.c. converters or other applications where the load is resistive. If the load consists of a fluorescent lamp which has a negative voltage/current characteristic then some form of ballast is required, and if the losses in such a ballast are to be kept low it must be reactive in character.

Considering first an inductive ballast, it is found that when the load on the inverter departs from a pure resistance, damaging transient voltage surges appear across the collector-emitter terminals of the transistors. These may be suppressed by the introduction of a capacitor directly across the primary of the transformer, but this has the adverse effect of increasing the switching time of the transistors, one of the results of which is to reduce the efficiency of the circuit to well below the theoretical maximum.

The other form of reactive ballast that can be considered is a capacitor, but then it is found that when a square-wave voltage is applied to a circuit consisting of a capacitor and fluorescent lamp in series, the resultant lamp current waveform is extremely peaky. This results in a low light output and a short lamp life.

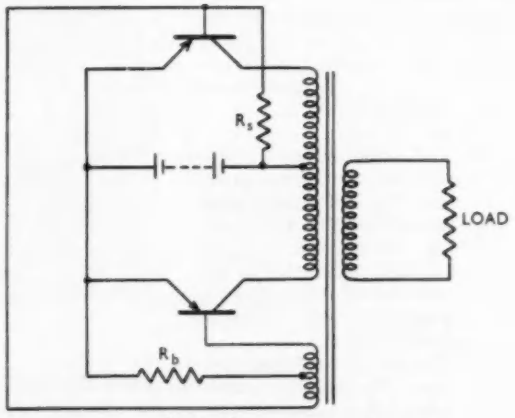

Fig. 1.—Square-wave inverter.

An alternative to a square-wave circuit is an inverter having a tuned transformer with the transistors acting as Class B, or preferably Class C, amplifiers[2], and such a circuit, complete with a fluorescent lamp load is shown in fig. 2. The lamp and its associated inductive ballast are connected across a high-voltage secondary of the transformer. Across the same winding is the capacitor C_T, which can be considered to act partly to correct the lamp load to unity power factor, and partly to tune the transformer to the required frequency. The drive current to the bases of the transistors is adjusted to suit the load and the gains of the transistors by means of the resistor R_b, which is shunted by capacitor C_b. While the transistor is conducting, this

capacitor is charged via the base-emitter diode in such a sense as to bias the transistor back towards cut-off. This gives a conduction angle of less than 180°, with a resultant increase of efficiency. Push-pull tuned inverters of this type can have efficiencies as high as 75%.

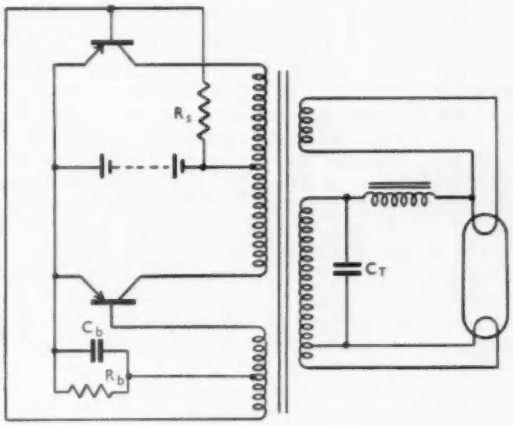

Fig. 2.—Sinusoidal inverter with fluorescent lamp load.

DESIGN CONSIDERATIONS FOR TUNED INVERTERS.

VOLTAGE.

The basic sinusoidal lamp inverter shown in fig. 2 can be designed to operate satisfactorily at direct voltages up to the limit set by the transistor breakdown. For a typical power transistor (GET. 573) this will normally be up to 40 V but can be extended up to 60 V with the use of selected transistors. For higher voltage working the transistors may be connected in series, providing suitable voltage-sharing networks are employed, but a circuit which has proved more satisfactory is that given in rather simplified form in fig. 3. A half-battery voltage point is provided by the network R_1 C_1 and R_2 C_2 and the primary of the transformer is connected between this point and the junction of the two transistors. This circuit has the advantages of halving the voltage stress on the transistors, while retaining a circuit which is essentially push-pull in character[3]. Based on these techniques, inverters have been designed to operate from battery voltages up to 110 V.

CURRENT.

The peak collector current of a transistor is usually specified as the current at which the current gain of the device falls below a certain arbitrary value. This will limit the maximum power obtainable from an inverter, although in practice the maximum power is usually limited by thermal considerations. In a Class C circuit the peak collector current rating will determine the minimum conduction angle, and hence the maximum efficiency, since, for a given output, as the conduction angle becomes less the peak current will increase.

FREQUENCY.

Several benefits may be obtained by making the frequency of an inverter fairly high. For example, the luminous efficiency of the lamp will increase with increasing frequency from about 300 c/s until it levels out at around 20 kc/s[4]. For a 40 W lamp the efficiency at 20 kc/s is some 12% greater than that at 50 c/s. The higher the frequency the smaller and lighter will be the gear and the easier it becomes to suppress the audible noise emitted by the wound components. In practice, the maximum frequency will be limited by the relevant cut-off frequency of present-day power transistors, which is around 7-8 kc/s. Where weight is of prime importance, as it is in inverters for aircraft applications, it has been found possible to operate the transistors at reduced power at frequencies considerably above the cut-off frequency. This is, however, expensive and where economics are more important frequencies as low as 1 kc/s are chosen.

D.C. SUPPLIES.

The designer of equipment to operate from battery supplies will have to cope with a range of input voltages. For example, the 24 volt batteries found on most of the steam- and diesel-hauled trains have a voltage range of from 22 volts up to 32 volts. In addition, due to the presence of inductive components such as relays and solenoids, high-voltage pulses, up to four or five times the battery voltage, may occur on the d.c. line. These

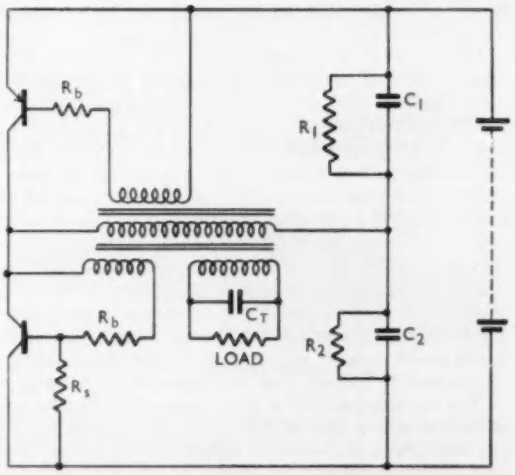

Fig. 3.—50 volt sinusoidal inverter.

pulses may be easy to suppress, usually by the addition of a large capacitor across the d.c. input, but occasionally the presence of higher energy pulses, such as are encountered in aircraft, may necessitate the design of inverters capable of withstanding the higher voltages.

THERMAL PROBLEMS.

The rapid dissipation of heat generated in the

transistor is an important problem in equipment using power transistors. In a fluorescent lamp inverter the losses in the transistors may account for between 15 and 25% of the total power input and some form of heat dissipator or 'heat sink' will be required. In some applications, the metal case surrounding the equipment may provide sufficient surface area for adequate cooling, but in others, such as the inverter shown in fig. 8, special fin assemblies may be necessary. The design of these fins has been adequately covered elsewhere[5], but fig. 8 shows the method used to obtain a large surface area in a small overall volume.

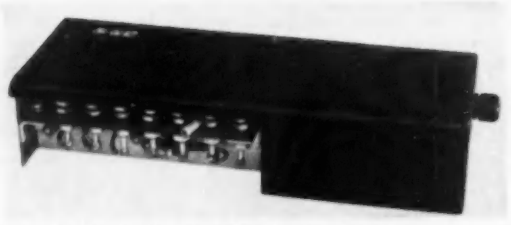

Fig. 4.—Prototype inverter for aircraft applications.

ENGINEERING DEVELOPMENT.

Each type of installation requires the use of techniques evolved as a result of the design considerations discussed above. Selection of the techniques to be employed is governed by the conditions under which the finished product is to operate.

The circuit to be employed is initially determined by consideration of the ratings of available power transistors, together with the supply voltage input and the required power output. The best use of a transistor in a circuit is obtained when the duty it is to perform fully utilizes the ratings given to the various limiting parameters. In a practical circuit the optimum operation of the transistors is likely to be limited either by thermal considerations or the current capacity of the transistors. Thermal performance is largely controlled by the details of mechanical design in the construction of a unit, and it may be possible to provide adequate cooling to allow the transistors to be used up to the maximum power rating, and also to satisfy their thermal requirements, if there is no limitation in size or weight.

The development of a unit is not completed by the evolution of a circuit which is designed to ensure that the transistors are stressed within the ratings of their limiting parameters. The rating of other components requires careful consideration, and in particular the rating of the capacitors which are to be used requires close attention. The transformer design includes suppression down to a negligible level of the acoustic noise emanating from the core.

Initially, the power output of the best transistors available was only just adequate for the operation of the smaller fluorescent tubes. However, due to the continued improvement in transistor manufacturing techniques, a wide range of suitable power transistors is now available, and by using appropriate components in each basic circuit it is possible to produce inverters to cover a greater variety of output requirements.

PRACTICAL APPLICATIONS.

Aircraft Lighting.

A Push-Pull Circuit.

The first unit to be developed was designed to rely on a relatively cool mounting position, aided by thermal contact with a metallic member which could be regarded as a heat sink. It was compact and at the same time provided the required a.c. power for the running of a 3ft or 4 ft fluorescent lamp at a reduced level of brightness, suitable for use in the lighting of the passenger cabins in aircraft with an available power supply of 28 volts d.c.; approximately 16 watts of a.c. power was supplied to the fluorescent lamp.

The circuit employed two transistors in a push-pull oscillator, similar to the circuit shown in fig. 2, and operated at 1000 c/s. Weighing less than 1¼ lb, the unit was 7in. long by 2½ in. wide and 1½ in. high, and was totally enclosed except for the terminals, as shown in fig. 4.

The sensitivity of transistors to excess voltage or thermal loading required the aircraft manufacturer to make a closer investigation into the true nature of the nominal 28 volt battery line, and to ascertain the maximum ambient temperatures likely to be encountered. The results showed that a transistor inverter was required to withstand voltage and thermal conditions not catered for in the original design; a re-design was therefore essential.

Series Transistors and Cooling Fins.

The nominal supply voltage was found to vary between 21 and 32 volts. The fluorescent lamp was required to strike at a minimum battery voltage of 21 volts in an ambient temperature of −20° C, and the inverter was required to be self-cooling in an ambient of +55° C with the battery at 32 volts. Moreover, due to the large capacity of generating plant in relation to the capacity of the battery, overvoltage surges of up to 60 volts can appear on the d.c. line.

The unit designed to meet these conditions used a single-ended circuit, employing two transistors in series to withstand the overvoltage surges. The starting requirements are met by applying a sufficient voltage from the transformer secondary to the fluorescent lamp, through an inductive ballast of the value necessary to maintain the required lamp operating conditions. The thermal conditions imposed by the ambient temperature, coupled with the losses in the transistors, demanded a large cooling area. The result was a unit provided with cooling fins to dissipate the excess heat by convection. Weighing 3¼ lb, the unit was 12 in. long by 5 in. by 2⅞ in. The fins were essential to the reliable performance of the unit within the specified maximum transistor junction temperature, yet it was bulky and heavy. A solution to the size and weight problem became necessary.

A Light-Weight Unit.

An improvement of the transistor thermal characteristics enabled the cooling fins to be removed and this resulted in the development of the relatively light-weight unit shown in fig. 5. It employs a circuit similar to that of the finned version, but weighs only 2 lb, and is 9½ in. long by 2¾ in. by 3¾ in. The construction allows air to circulate freely past the components and over both sides of the chassis, giving satisfactory thermal conditions.

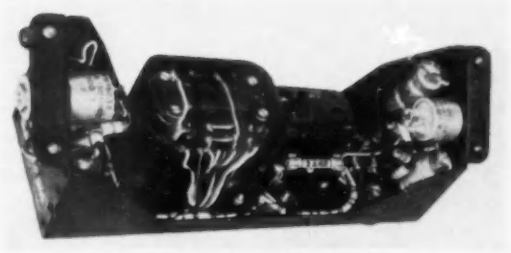

Fig. 5.—1 kc/s inverter for aircraft.

As with the earlier finned version, the use of 1000 c/s as the frequency of inversion can give rise to an [illegible] tionable acoustic noise, largely caused by magn[illegible] striction in the nickel-iron laminations used in [illegible] wound components. The requisite damping is achieved by encapsulation of the transformer and ballast in a polymerized oil[6], as can be seen in fig. 5.

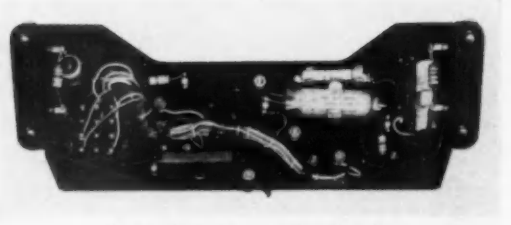

Fig. 6.—15 kc/s inverter for aircraft.

As soon as power transistors were produced capable of operation at higher frequencies, the advantage of reducing the size and weight of iron-cored components was exploited. At the same time it was found possible to increase the frequency of operation to about 15 kc/s, above the range of the human ear, removing the necessity for encapsulation. The circuit has been changed to include a pair of transistors operating in push-pull, selected to withstand individually the voltage stresses imposed by surges on the d.c. supply. The resultant economy in components gives an improved layout, as shown in fig. 6. Weighing no more than 1 lb, the unit is the same size as the inverter shown in fig. 5, and is interchangeable with it. A variation of this unit is required to provide switching of the a.c. output to either of two fluorescent lamps; one being of a warm colour and the other of a cool colour. Relays to do this are added in the available space within the unit. The extra weight and expense of supplying warm lighting in cold climates and cooler lighting in warmer climates is indicative of the consideration given to airline passengers.

RAIL AND ROAD TRANSPORT LIGHTING.

Although both aircraft and trains can operate in the hottest parts of the world, in railway coaches there is generally a greater freedom to mount a unit away from potential sources of excess heat, and space for cooling is more readily available. The conditions imposed by the nature of the supply are also not so arduous as those prevalent in the aircraft industry, and for these reasons inverters designed for railway applications using the early power transistors were capable of a somewhat higher output than those designed for aircraft use.

28 Volt 20 Watt Inverter.

The first transistor inverter units for public transport service consisted of a single 2 ft 20 watt fluorescent lamp in a fitting surmounted by the inverted unit, as shown in fig. 7. In this arrangement the combining of the inverter with the lighting fitting provides the required cooling area. The unit is similar to the inverter shown in fig. 5, in that it employs encapsulation in a polymerized oil to reduce acoustic noise. The circuit uses a pair of transistors connected in push-pull and oscillating at 1000 c/s.

28 Volt 40 Watt Inverter.

Instead of striving for a better engineering solution to the problem of providing a given quantity of power,

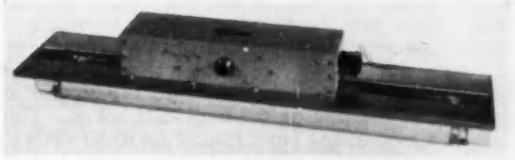

Fig. 7.—20 watt inverter for railways.

as with the development of transistor inverters for the aircraft industry, the application of development for rail and road use has been to provide an increasing power output from a basic circuit. The subsequent availability of improved transistors enabled the power output of the basic push-pull circuit to be increased to 40 watts.

The first 40 watt unit employed the technique of thermally isolating the transistors from the other components, thus alleviating the cooling problem of the transistors themselves. At the same time the heat dissipation in the remaining components was allowed to give a temperature rise beyond the limit for transistors, but within the rating of the components con-

cerned. As can be seen in fig. 8, the cooling of the transistors is provided by the convection cooling of a fin on which each transistor is mounted. Although the frequency remains at about 1000 c/s, the use of silicon-iron laminations significantly reduces the noise caused by magneto-striction, and the transformer and ballast choke no longer require encapsulation. The overall dimensions of the unit are 9 in. long by 5 in. by 5½ in. and it weighs 6¼ lb.

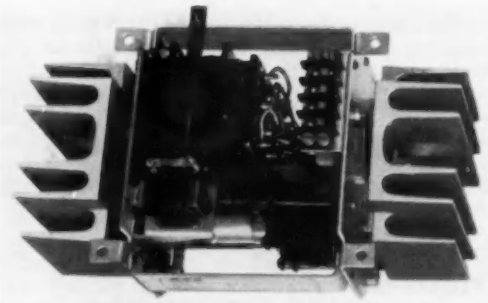

Fig. 8.—40 watt inverter for railways.

A re-design of the 40 watt unit using the latest transistors enables the cooling fins to be removed and the inverter is now housed in an enclosed case, 9 in. long by 2½ in. by 3¼ in., and weighing less than 1¾ lb. This unit also provides a further heater supply, enabling it to operate either one 4 ft fluorescent lamp or two 20 watt lamps in series.

28 Volt 80 Watt Inverter.

If adequate cooling is provided, a push-pull inverter, using the latest transistors, will deliver 80 watts. Inverters of this type have so far been used in applications where they have been required to supply a number of small low-wattage lamps. They have, therefore, been designed as power packs with a sinusoidal a.c. output, and separate ballast gear is provided as required by the individual lamps. This enables a total mixed lump load of up to 80 watts to be supplied from one inverter.

HIGHER INPUT VOLTAGES.

In many installations, such as steam- or diesel-hauled railway stock, the 28 volt supply is standard, but on Underground, suburban and main line stock equipped with electric traction a 50, 70 or 110 volt battery may be fitted for train control. Lighting inverters have been designed to make use of these supplies.

50 Volt 40 Watt Inverter.

The 50 V inverter circuit is an application of the split-battery techniques, shown in fig. 3, which enable the input voltage to be divided equally between a pair of transistors. The unit has been adapted from the basic push-pull 40 watt inverter, shown in fig. 8.

An alternative assembly has been designed for use in the conditions prevailing on Underground trains, where there is a requirement for an emergency source of light supplied from the 50 volt battery, which will continue to operate in the case of a traction voltage failure. The inverters are used to operate continuously certain lamps in each coach, at the same brightness as the bulk of the fluorescent lighting which is provided from the traction supply.

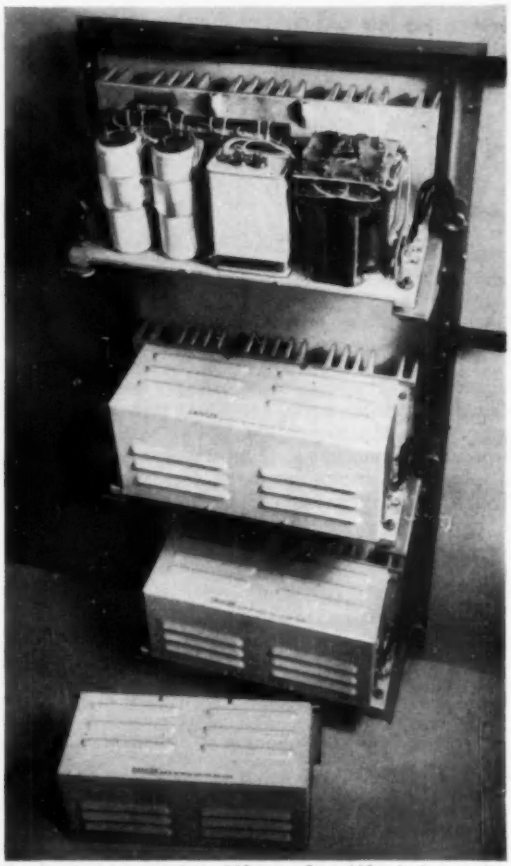

Fig. 9.—Inverters supplying 160 watts from 110 volt d.c. supplies for railway use.

This technique, and other modifications of it, are suitable for supplying stand-by or emergency fluorescent lighting in any situation where a battery supply is available, with the added advantage of improved efficiency as compared with an incandescent lamp load.

110 Volt 160 Watt Inverter.

Railway stock for use on the 25 kV overhead electrification schemes is among that which uses a 110 volt battery. By combining the split-battery technique

Fig. 10.—Lighting in an open saloon coach operated from 110 volt d.c. inverters.

with the technique of sharing a voltage stress between two transistors in series, it is possible to design an inverter to operate from a 110 volt supply. The units shown in fig. 9 are designed as power packs each operating four 4 ft lamps with individual ballast gear. The four transistors are mounted in the finned face of the chassis, which weighs 17½ lb, and is 14½ in. long by 6½ in. by 6 in. Fig. 10 shows a lighting installation using equipment of this type in an open saloon multiple-unit coach.

Further developments of this unit seem possible; one transistor inverter should be able to supply up to about 250 watts, sufficient to provide fluorescent lighting for half a railway coach. The double source of power has the advantage that if one unit should fail the coach will not be in complete darkness.

Other Variations.

The available transistors now include types which enable suitable units to be designed for lower output powers and lower input voltages. This need is being met with small inverters, for single or twin lamp working, from 28 or 12 volt supplies. These units are particularly suitable for road vehicles of all types, including private cars, and caravans. Use has also been made of such inverters in small pleasure boats.

The lower power range of inverters include a family of units using single transistor circuits. This range of inverters is identical in construction and appearance and caters for the operation of lamps of 20 watts or less in three versions:

(*a*) One 2 ft. 20 W or 18 in. 15 W lamp.
(*b*) One 12 in. 8 W or 9 in. 6 W lamp.
(*c*) Two 12 in. 8 W or 9 in. 6 W lamps in series.

The components are mounted in a totally enclosed case, 9¼ in. long by 1½ in. by 2¼ in.

The same circuit and assembly also covers 12 volt applications in the following three versions:

(*a*) One 18 in. 15 W lamp.
(*b*) One 12 in. 8 W or 9 in. 6 W lamp.
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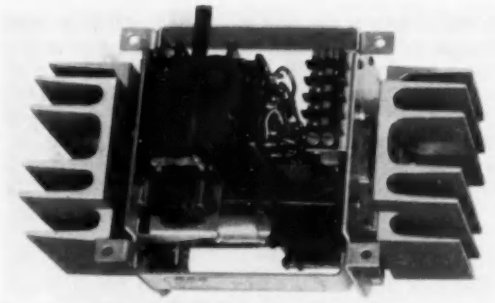

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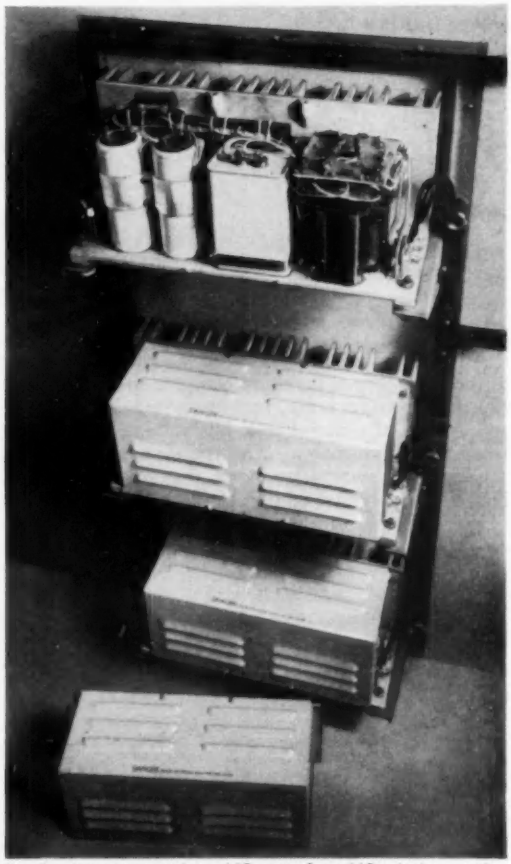

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FUTURE DEVELOPMENTS.

The most promising field for future developments of inverters for fluorescent lamps appears to lie with the *p-n-p-n* switch, or silicon controlled rectifier[7]. The thyratron-like properties of this device means that the circuit operation is essentially square wave, giving an inherent high efficiency. The commutating capacitor which is normally connected across the primary of the transformer effectively prevents high-voltage peaks occurring across the devices and, unlike the square-wave circuit using transistors, this capacitor will not increase the switching time, since this is a function of the device alone. Hence, this circuit maintains its high efficiency even when used with reactive loads.

A typical parallel inverter using a pair of silicon controlled rectifiers driven from a blocking oscillator is shown in fig. 11. An experimental inverter of this type, operating from a 28 volt battery, has satisfactorily operated a load of 12-40 watt lamps.

Another possible future application lies in the use of transistors or silicon controlled rectifiers in frequency converters to operate fluorescent lamps at high frequency in situations where 50 c/s supplies are already available. If the frequency converter can be made efficient and cheap the operation of lamps at high frequency offers substantial advantages such as small, cheap, ballast gear and an increased luminous efficiency. Work on this aspect is not, however, sufficiently well advanced to discuss it in detail in this article.

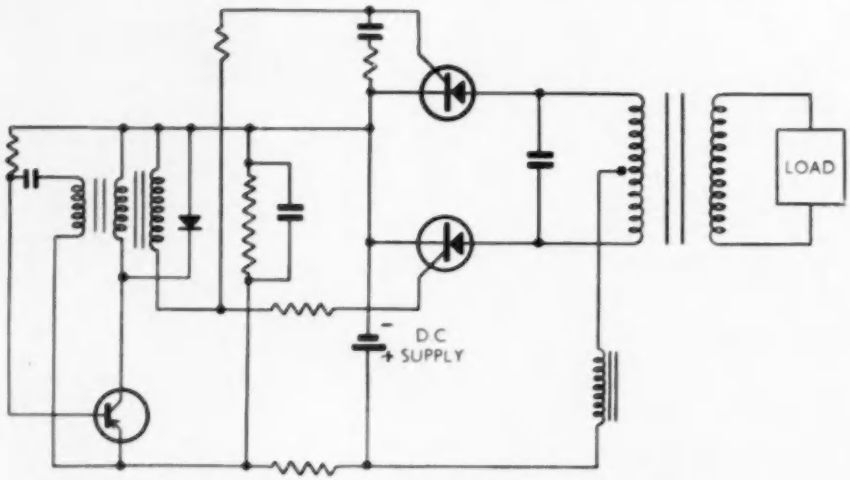

Fig. 11.—Driven inverter using silicon controlled rectifiers.

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7. 'Notes on the Application of the Silicon-Controlled Rectifier' ECG-371-1, (General Electric Co., New York, 1958).

Multiple-Unit Train Equipments

for

Liverpool Street — Enfield-Chingford — Hertford-Bishop's Stortford Lines

By R. LEDGER, B.Sc.(Tech.), A.M.I.E.E., and J. C. TURRALL, A.M.I.E.E., Traction Division.

This paper is one of a series presented at the British Railways 25 kV a.c. Electrification Conference held in London in October 1960. It describes the electrical equipment for B.R. three- and four-coach multiple-unit trains operating on a 25 kV a.c. supply and incorporating G.E.C. Com-Pak mercury arc rectifiers.*

At the same conference a paper on the G.E.C./N.B.L. 25 kV electric locomotives was presented by Mr. W. D. Morton, Manager, Traction Division, and Mr. H. W. Scott, Chief Designer, North British Locomotive Co. Ltd. These locomotives were described in the Spring 1960 issue of the 'G.E.C. Journal.'

INTRODUCTION.

THIS multiple-unit stock ordered by the British Transport Commission from The General Electric Company Ltd. is of two types designed for routes having different service requirements.

Fifty-two three-coach units, each comprising a battery driving trailer, motor coach and driving trailer, will operate from Liverpool Street to Enfield Town and Chingford. This is a high-density suburban service with, in the case of the Enfield Town route, a scheduled speed of 22·2 mile/h and an average of only three-quarters of a mile between stops. The equipment must, therefore, be designed for a high frequency of operation and for handling the heavy currents at short intervals characteristic of this type of service.

Nineteen four-coach units, similar to the three-coach ones but with a trailer coach added, will operate an outer suburban service with an average speed of approximately 34 mile/h from Liverpool Street to Hertford and Bishop's Stortford. This service consists of a non-stop run of approximately 8½ miles followed by 22¼ miles with an average of 2 miles between stops, and as it involves a considerable amount of running near the maximum service speed the equipments must be designed for a high standard of performance in this region.

* The full proceedings of the Conference, including all papers and discussions, will be published by the British Transport Commission towards the end of 1960 at the price of £5. Orders should be sent to the Publicity Officer, British Transport Commission, 222 Marylebone Road, London, N.W.1.

The equipments are also required to operate in multiple with ones produced by three other manufacturers. A common driving procedure and layout of controls is used and the general disposition of the different makes of equipment on the coaches also follows a common plan.

The coaches were designed and built by British Railways, the three-car sets at York and the four-car sets at Doncaster.

Fig. 1 is a photograph of a train comprising two 3-car units.

LEADING PARTICULARS.

FOUR-COACH UNIT.

Vehicle	Unladen Weight	Laden Weight (all seats occupied)
Battery driving trailer	35·9 tons	40·9 tons
Motor coach	54·9 tons	60·9 tons
Non-driving trailer ...	31·0 tons	36·0 tons
Driving trailer	32·2 tons	39·0 tons
Total	154 tons	176·8 tons

THREE-COACH UNIT.

Battery driving trailer ...	34·1 tons	39·1 tons
Motor coach	54·2 tons	60·2 tons
Driving trailer	30·8 tons	37·6 tons
Total	119·1 tons	136·9 tons

Other principal data for the three- and four-coach units with all seats occupied (16 passengers taken as

Fig. 1.—Train comprising two 3-car units.

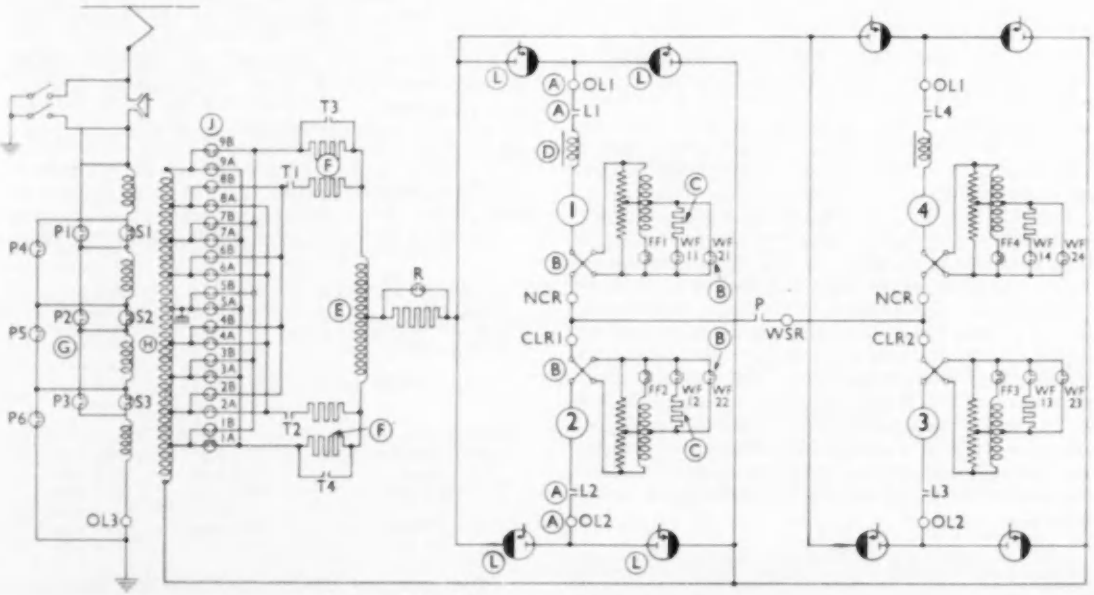


Fig. 2.—Diagram of main power circuits.

1 ton), a line voltage of 22·5 kV, 100% secondary tappings and half-worn wheels, are as follows:

	3-coach unit	4-coach unit
Maximum axle load	16·7 tons	16·7 tons
Maximum service speed	75 mile/h	75 mile/h
Balancing speed on level tangent track	72·3 mile/h	67 mile/h
Acceleration on level tangent track ...	1·38 mile/h/sec	1·1 mile/h/sec
Average accelerating tractive effort ...	21 600 lb	22 200 lb
Continuous rating at wheel in weak field		
Tractive effort ...	7000 lb	
Speed	43 mile/h	
Power	800 h.p.	
Total weight of electrical equipment	23·4 tons	23·5 tons

The performance curves for the equipments under the above conditions are shown in fig. 4, and the arrangement of the equipment on the motor coach underframe is shown in fig. 3.

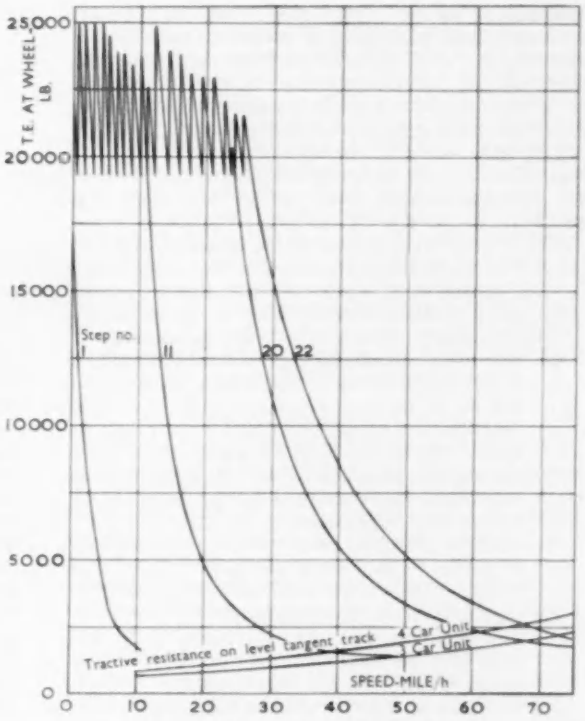


Fig. 4.—Speed tractive effort characteristics.

DESCRIPTION OF CIRCUITS.

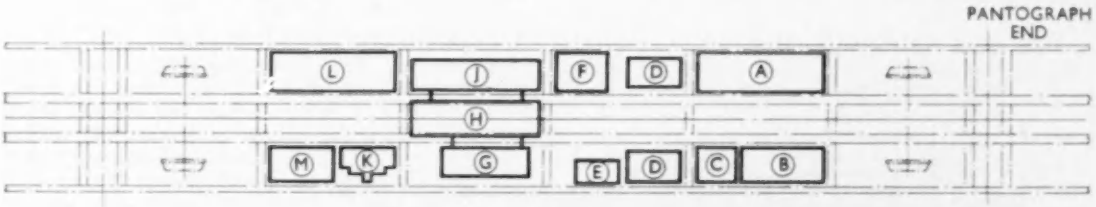
Power Circuits.

Fig. 2 shows the power circuits in schematic form. Current is fed from the pantograph through an airblast circuit breaker to the voltage changeover switch, which connects the four sections of the transformer primary in series for 25 kV operation and in parallel for 6·25 kV operation. The return current is fed from the transformer to the wheels through brushes on each axle of the motor coach.

The transformer secondary supplies two bridge mercury arc rectifier circuits, each feeding two traction motors in series. An equalizing connexion between the mid-points of each pair of motors reduces the rise in voltage on a motor which develops slip, and thus assists recovery of adhesion.

The motor voltage is controlled by tapping switches on the transformer secondary using two contacts per tap in conjunction with series resistors and a centre-tapped choke.

By these means 20 steps are provided from nine taps, two of these being running steps with no series



ITEM No.	DESCRIPTION
A	EQUIPMENT CASE. LINE SWITCHES & O.L. RELAYS.
B	EQUIPMENT CASE. REVERSER & W.F. CAM GROUPS.
C	RESISTANCE. WEAK FIELD.
D	MAIN MOTOR CHOKES.
E	TAPPING SWITCH CHOKE.
F	RESISTANCE. TAPPING.
G	SUPPLY CHANGE-OVER SWITCH CASE.
H	MAIN TRANSFORMER.
J	TAP CHANGING SWITCH.
K	TRANSFORMER OIL COOLER & FAN.
L	MAIN RECTIFIER.
M	RECTIFIER IGNITION EQUIPMENT.

Fig. 3.—Plan layout of equipment on underframe of motor coach.

resistance in circuit. Two further steps are provided by motor field weakening, of which the second is a running step. The motor field is permanently diverted for smoothing purposes, and the final step is obtained by a tapping on the field in conjunction with a proportionate tapping on the smoothing divert.

The earth connexion in the motor circuit is at the mid-point of the transformer secondary, thus limiting the potential to earth of all parts of this circuit to a maximum of half the full secondary voltage.

This scheme was adopted for the following reasons:

(*a*) The restricted space available for underframe-mounted equipment and the desirability of using a minimum amount of oil-immersed apparatus made low voltage tapping essential.

(*b*) The most economical arrangement of rectifiers and transformer is obtained with bridge connexion at an output voltage such that it is desirable to connect two motors permanently in series. Use of the bi-phase circuit could halve the number of rectifiers, but the advantages of this would be outweighed by the larger transformer and duplication of the tapping switch contacts and choke which would result from its adoption. The further alternative of a single bridge circuit using four rectifiers with four motors in series is unacceptable because of its poor adhesion characteristics, inability to operate with half the motors cut out in the case of a defect developing, and high secondary voltage.

(*c*) The scheme incorporates the following features considered essential for service on multiple-unit stock of this nature.

(*i*) Speedy operation through the sequence, particularly when returning to the off position.

(*ii*) Avoidance of backward tapping when switching off.

(*iii*) A small number of transformer tappings.

(*iv*) Reduction to negligible proportions of momentary voltage drops during notching.

(*d*) The scheme is a compromise between the simplicity of resistance control at constant voltage and the complete elimination of resistance steps, in that the introduction of some series resistance and reactance into the circuits during notching improves current distribution between motors and reduces the number of taps and steps required, without making the adhesion characteristics unacceptable for multiple-unit service.

Control Circuits.

Control of the direct current circuits follows established d.c. practice, with the addition that isolation of a pair of motors also cuts out the associated rectifiers by opening their excitation circuits. Movement of the master controller causes the tapping switch to progress step by step to the appropriate position under the control of a current limit relay which regulates the lifting of the pawls, the operation being described in more detail on page 197.

Auxiliary Circuits.

A 240 V tertiary winding on the main transformer supplies the train heaters, battery charger and auxiliary machines with the exception of the auxiliary compressor, which, together with the lighting and control circuits, is fed from a 110 V alkaline battery. The battery charger is a transductor-controlled rectifier unit with voltage regulation by a closed-loop control.

The main compressor is driven by a d.c. series motor supplied through a selenium rectifier, and the transformer and rectifier pumps and fans by single-phase capacitor motors. Fig. 5 shows the auxiliary circuits.

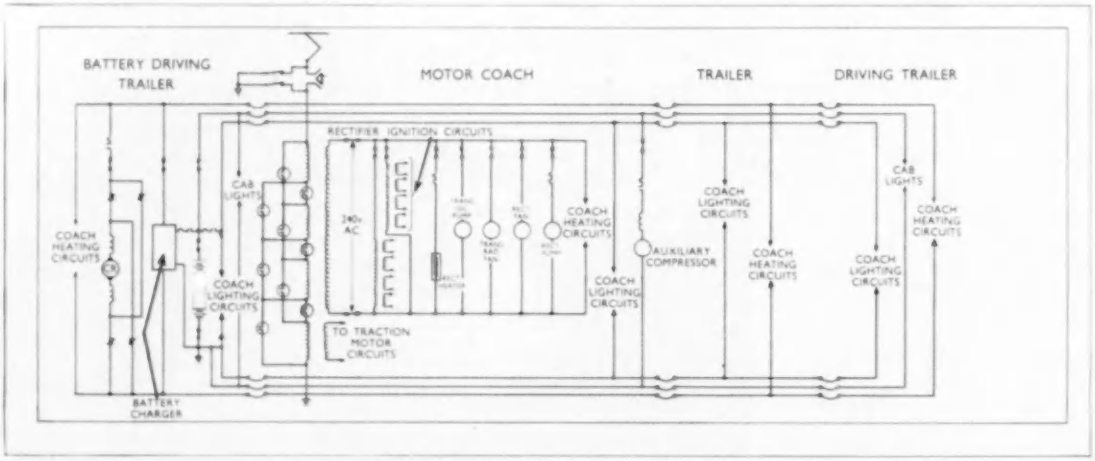


Fig. 5.—Diagram of auxiliary circuits (4 car train).

DESCRIPTION OF ELECTRICAL APPARATUS.

H.V. EQUIPMENT.

Circuit Breaker and Pantograph.

These are common to all types of rolling stock and have been described in other conference papers.

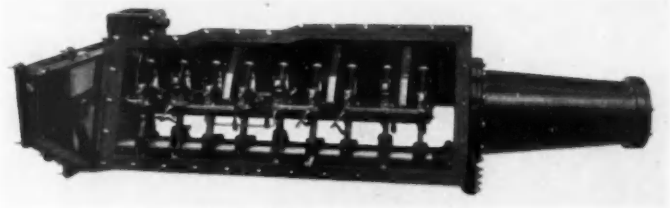


Fig. 6—Voltage changeover switch.

H.V. Lead in.

The 25 kV feed from the pantograph is by bare conductor to the circuit breaker and thence to the through insulator on the roof. A continuous cable goes from the insulator to a compound-filled connexion box formed in the voltage changeover switch housing.

Voltage Changeover Switch.

This is a nine-pole oil-filled switch with contactor type elements operated by insulated links from a common shaft which is rotated to either of two positions by an external air engine. The switch, illustrated in fig. 6 is flange mounted on the transformer but has a separate oil supply to avoid any contamination of the transformer oil.

TRANSFORMER.

The transformer rating to I.E.C. 77 is as follows:

Primary ...	...	25 6·25 kV	1000 kVA
Secondary	...	1875 V	910 kVA
Tertiary ...	...	269 V	90 kVA

The oil-cooled transformer (fig. 7) is the heaviest single item on the underframe and it is therefore logical to mount it in the centre bay, which necessitates a long narrow shape.

This requirement is best met by a two-limb design with the coil axis horizontal, and because this type of construction does not allow oil circulation by thermo-syphon action, forced circulation with a very high rate of flow is used in conjunction with a separate fan-cooled radiator, the oil being directed into the transformer winding by a system of baffles.

The core is, in effect, clamped between two frames with the weight and shock loads carried on key bars at each corner, thus avoiding heavy stresses on the core bolt insulation. The complete transformer is suspended from resilient mountings on the underframe by extensions of these frames, thus permitting slight relative movement between it and the underframe. The majority of the oil piping is rigidly mounted on the transformer, only short lengths of flexible hose being used for the radiator connexions.

The impulse level for the 25 kV connexion was specified as 170 kV peak. It was not considered necessary to maintain this level for the 6·25 kV connexion and a useful weight saving was effected by reducing the level to 75 kV peak under these conditions.

TAPPING SWITCH.

This is an electro-pneumatic camshaft-operated switch with cam opened, spring closed, contacts; a design which provides the necessary number of steps with the minimum of electrical interlocks. Adequate mechanical spacing between steps is obtained by using two camshafts, each with its own air engine, which, when notching up, move alternately under the control of a common escapement mechanism, shown diagrammatically in fig. 8.

Lifting of a pawl by energizing its control valve operates pawl interlocks, causing rotation of the camshaft by exhausting one cylinder of its air engine. Dropping of the pawl cushions the stopping of the shaft by re-admitting air to the cylinder. Starting and stopping is therefore without trigger action or undue impact. The pawl drop position is determined mechanically by the notch wheel and accurate setting of the electrical interlocks which de-energize its valve is unnecessary.

The interlocks controlling switch operation and providing safety features are cam-operated by extensions of the main shafts and have silver butt-type contacts.

Return to the lowest tap position is made, without going through the tapping sequence, by using contactors to break the circulating current path. This

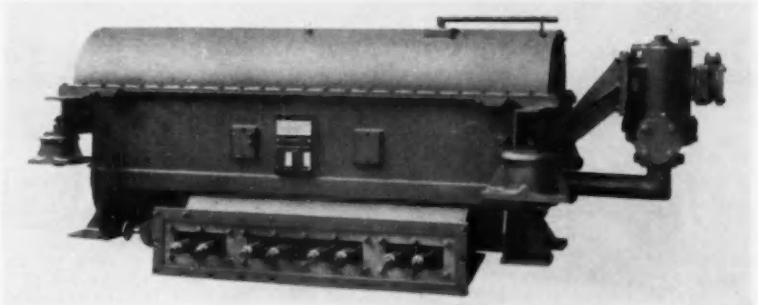


Fig. 7.—Transformer.

allows a very quick reset time, as both camshafts run back simultaneously. The complete switch is illustrated in fig. 9.

RECTIFIERS.

Eight Com-Pak single-anode rectifiers arranged in two bridge circuits are fitted to each motor coach. They are a somewhat smaller version of the rectifiers used in the 25 kV a.c. locomotive*, and have a simpler cooling system consisting of a single circuit from the radiator through the cathode, tank and anode in

* *G.E.C. Journal*, Vol. 27, p. 71, Spring 1960

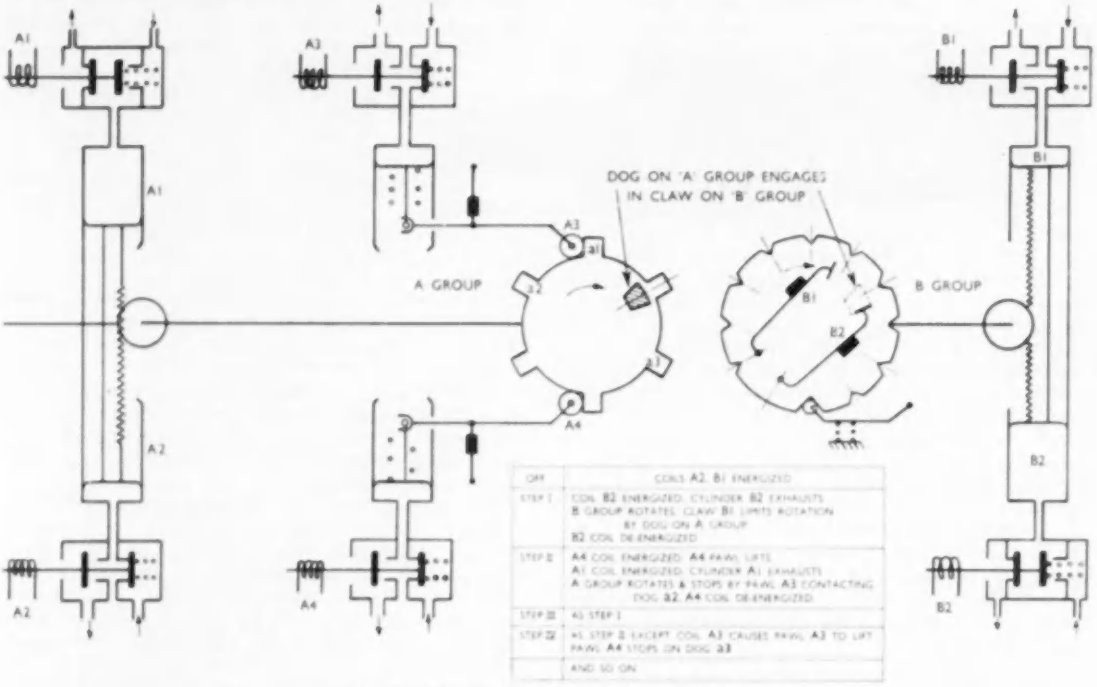


Fig. 8.—Diagram of tapping-switch mechanism.

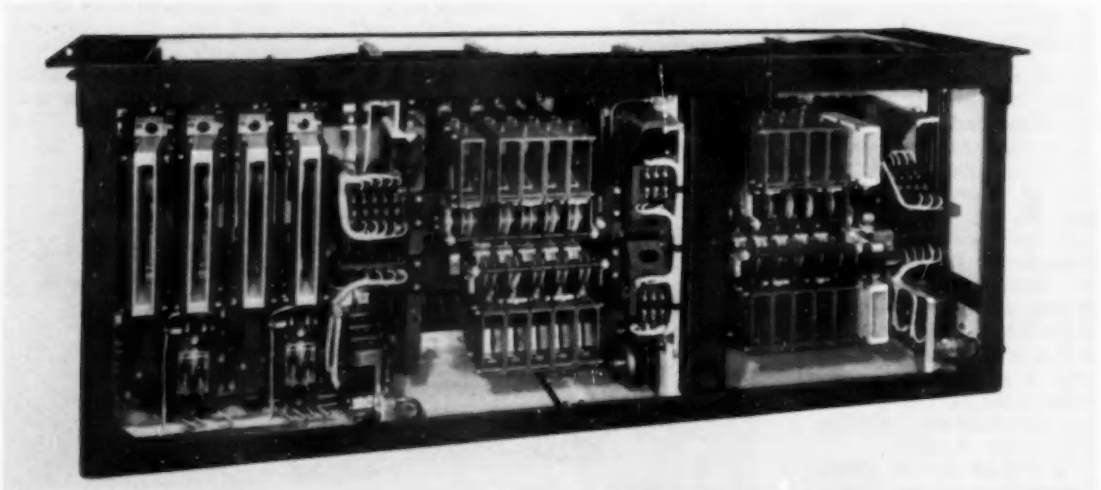


Fig. 9.—Tapping switch.

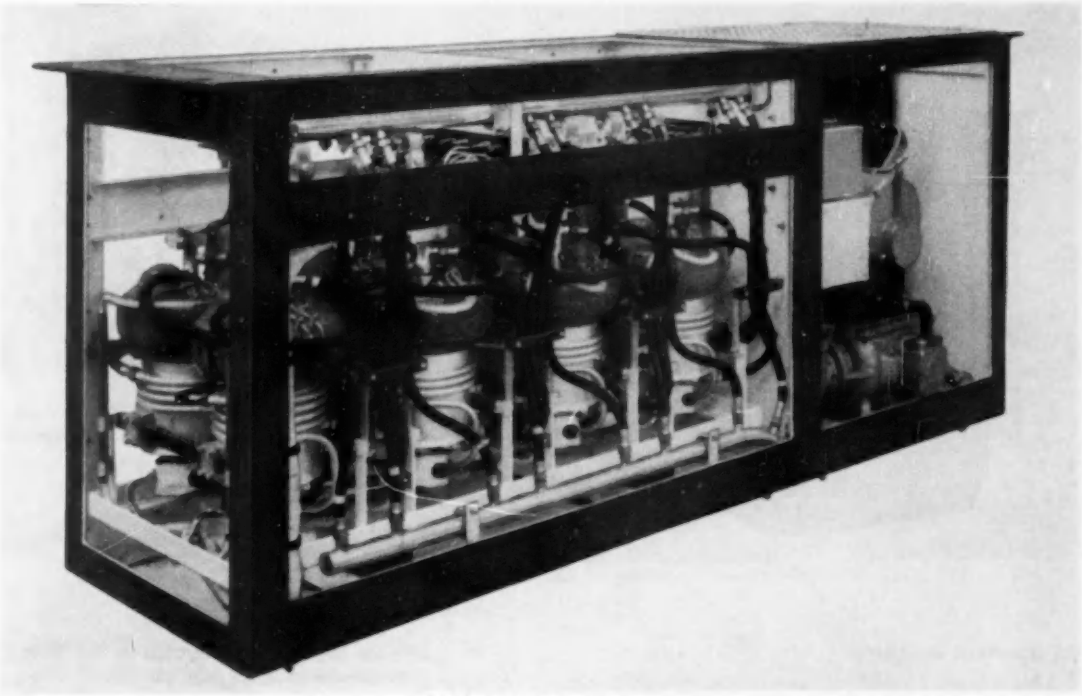


Fig. 10.—Rectifier assembly.

series. Fig. 10 shows the rectifiers mounted in their case.

Chokes.

The smoothing and tapping switch chokes are natural-oil-cooled air-gap reactors. Two smoothing chokes, each of 0·016 H inductance at 230 amp d.c. are used and are designed to limit the motor current ripple to 30% at any current between half and twice the continuous rating.

Traction Motors.

The axle-hung motors follow conventional d.c. practice except for the following features:

(*a*) They are approximately 5% heavier than an equivalent d.c. motor, having been made 7% larger in diameter and somewhat shorter in length in order to improve commutating conditions.

(*b*) A permanent field divert of 10% is used to reduce flux pulsation to approximately 2%, which eliminates its harmful effect on commutation and losses.

(*c*) Eddy currents are reduced to a minimum by using thin pole stampings and by designing the coil springs and washers to give the maximum resistance to circulating currents produced by the pulsating armature and inter-pole fields.

Class B insulation is used because the advantages of a smaller motor resulting from operation at Class H temperatures are outweighed by its increased cost and more difficult commutating conditions.

Auxiliaries.

The following are the principal particulars of the auxiliary machines:

Function	No. Unit	Output	Supply	Motor Data h.p.	rev/min	Type
Main compressor	1	38 ft³/min swept vol.	240 V a.c.	7·0	1200	d.c. series with rectifier
Auxiliary compressor ...	1	5 ft³/min swept vol.	110 V d.c.	0·75	1080	d.c. series
Transformer coolant pump ...	1	50 gal/min against 20 ft hd.	240 V a.c.	1·5	1450	Single phase induction, capacity start and run.
Transformer radiator fan ...	1	2500 ft³/min		0·4	1450	
Rectifier coolant pump ...	1	9 gal/min		0·75	2900	
Rectifier radiator fan ...	1	2500 ft³/min		0·4	1450	
Battery charger	1	8·0 kW at 110 V d.c.	Westinghouse Type 1285			

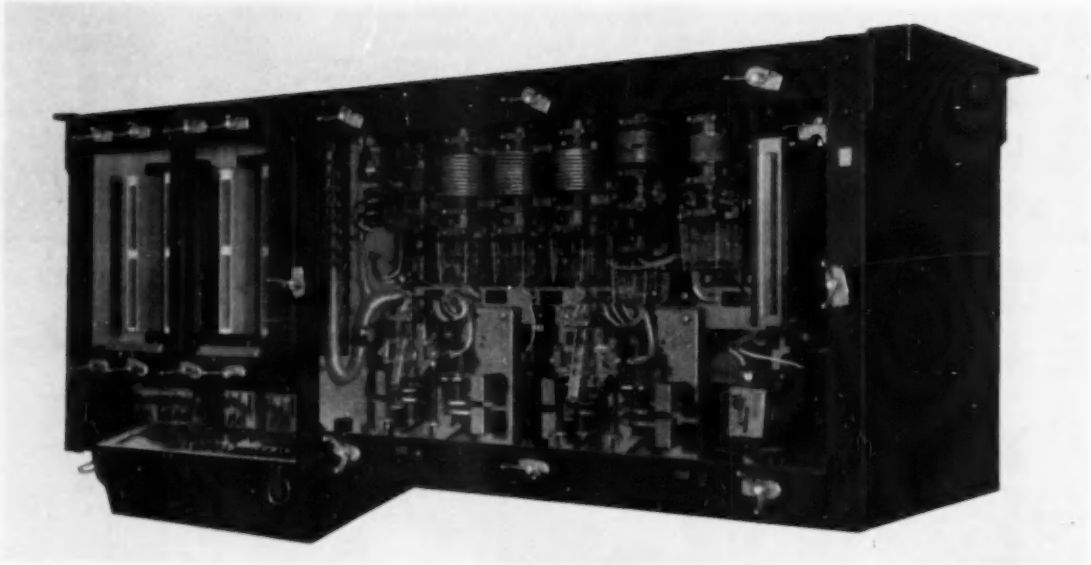


Fig. 11.—d.c. equipment.

D.C. Control Equipment.

This follows established d.c. traction practice but incorporates modifications to those relays which operate on pulsating current. The equipment, shown in fig. 11, is electro-pneumatically operated, camshafts being used for the reverser and field control group, with individual contactors elsewhere.

Master Controller.

Silver butt contacts, spring closed and cam opened, are operated by a rocking dead man's handle and interlocked reverse handle, freed for operation by a removable key.

PROTECTION.

The circuit breaker cannot be closed unless its operating air pressure and the transformer oil level are correct, the voltage changeover switch and measuring relays are in corresponding positions, and the motor circuits are open. The breaker is tripped by low air pressure, low transformer oil level, operation of the primary overload relay or loss of line voltage.

The motor contactors cannot be closed unless the rectifier coolant pressure and temperature, and the transformer oil temperature are correct. The contactors are opened if the rectifier coolant pressure becomes too low, or its temperature either too high or too low, or if the transformer oil becomes overheated, or by operation of the motor overload relays. The latter protect the motor circuits against overload or limited short-circuit, major faults on the motor circuits and all faults on the rest of the secondary circuit being cleared by the primary overload relay.

Protection of the auxiliary circuits is by H.R.C. fuses, except for the rectifier ignition circuit where a combination of automatic and manually closed thermal relays prevents damage to the ignition solenoid should a rectifier fail to ignite.

No-voltage protection on the primary circuits is provided by the voltage measuring relays opening the circuit breaker. The traction motor circuits are protected by a combined no-voltage, no-current relay energized and retained up to the half-voltage tapping by the closing of the circuit breaker. Beyond half-voltage the relay is retained by motor current only.

The voltage measuring scheme is protected against failure of the d.c. supply to the slave relays by a no-voltage relay with contacts in the feed to the a.c. measuring relays. Wheel slip protection is provided by means of a relay in the equalizing connexion between the pairs of motors. Operation of the relay prevents further progression of the tapping switch.

CONCLUSIONS.

These electrical equipments have been designed to give reliable operation on two widely differing types of service, and in addition they have met the requirements laid down by the B.T.C. for multiple working with other multiple-unit stock, and for the general design of the equipments. In order to do this much development work was necessary, particularly as regards the rectifiers and tapping switch, which it has been quite impossible to describe fully in the necessarily brief confines of this paper. Satisfactory trial running confirms the correctness of the decisions taken and promises successful operation under full service conditions.

Synchronous Condensers for Australia

By H. L. BARNARD, B.E.(Adel.)M.I.E.E., M.I.E.Aust., A.M.I.Mech.E., Chief Electrical Engineer, and J. S. DARBY, A.M.I.E.E., A.M.I.E.Aust., Contracts Engineer, British General Electric Co. Pty. Ltd., Sydney.

ONE of the largest synchronous condenser installations in Australia, comprising four G.E.C. 20 MVA machines, has recently been put into service for the Electricity Commission of New South Wales, at Carlingford, a main substation on the western fringe of Sydney.

condensers were originally ordered by the Department of Railways for use in its own transmission system, but in 1950 an act of Parliament established the Electricity Commission of New South Wales, which became responsible for the generation and transmission of electrical energy over an area previously supplied by

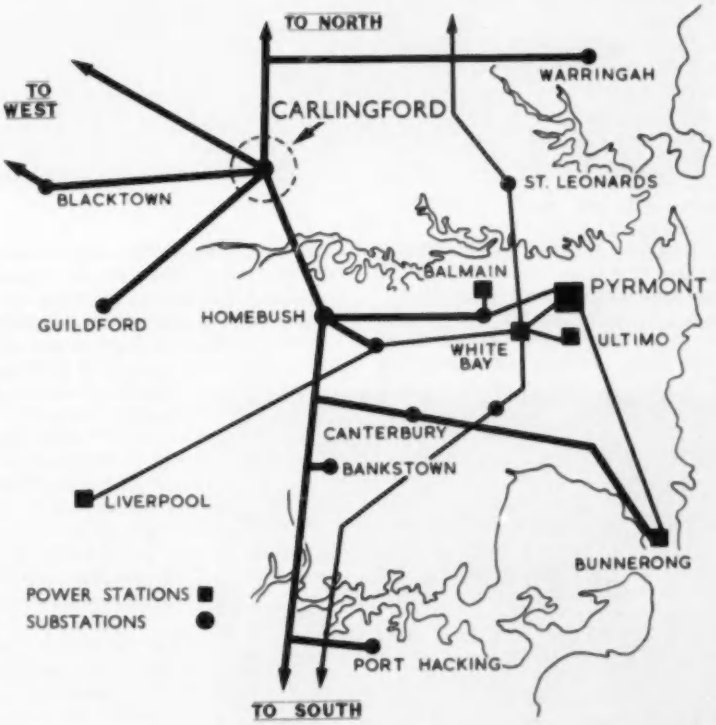


Fig. 1.—Map showing the location of power stations, substations and transmission lines in the Sydney Metropolitan Area.

Carlingford forms the focal point of a widespread electrical transmission system, being linked to new major power stations to the north, south and west of the State and to the Sydney metropolitan power stations via Homebush switching station (fig. 1). The

four major independent bodies including the Department of Railways.

Since the formation of the Commission, more than 1000 MW of generating plant has been installed in existing power stations and in ten new ones, 1000 miles

of major transmission line have been constructed and eighteen major substations brought into service. The growth in the transmission system has, to a large extent, been due to the location, for economic reasons, of the new large generating stations on the coalfields rather than near the load centres.

Additional generating plant is installed in new power stations which have been built at Lake Macquarie in the north, Tallawarra in the south and at Wallerawang to the west. All of these stations are situated near the coalfields and are within 100 miles of Sydney. The stations are being extended and are planned for capacities of 330 MW, 320 MW and 240 MW respectively. Part of their output is transmitted to the Sydney area at 132 kV and the Carlingford synchronous condenser installation supplies a major part of the reactive power required for this transmission. The remainder of the reactive power required is supplied by static capacitors connected to the 33 kV system.

Larger steam power stations are projected for the northern coalfields. Construction of one of these stations has commenced at Vales Point on Lake Macquarie. The Sydney metropolitan power stations will not be extended but will be relegated gradually to peak load and reserve duties as more efficient plant comes into service.

The output of the large projected stations and the output of the Snowy Mountains Hydro-electric stations will be transmitted at 330 kV. Further large synchronous condenser installations are required for this power transmission and recently tenders for two 75 MVA outdoor synchronous condensers have been called for.

The control system for starting, stopping and operating the condensers is designed for automatic operation. At the present time the condensers are controlled by the operating staff at Carlingford Substation but later, when the new system control centre, which it is planned to build on the site adjoining the substation, is in operation, control of the machines will probably be transferred to the new centre.

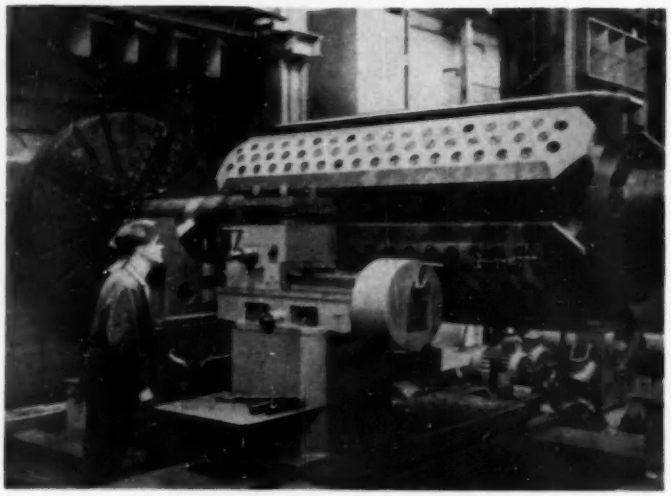


Fig. 3.—Rotor body in course of machining.

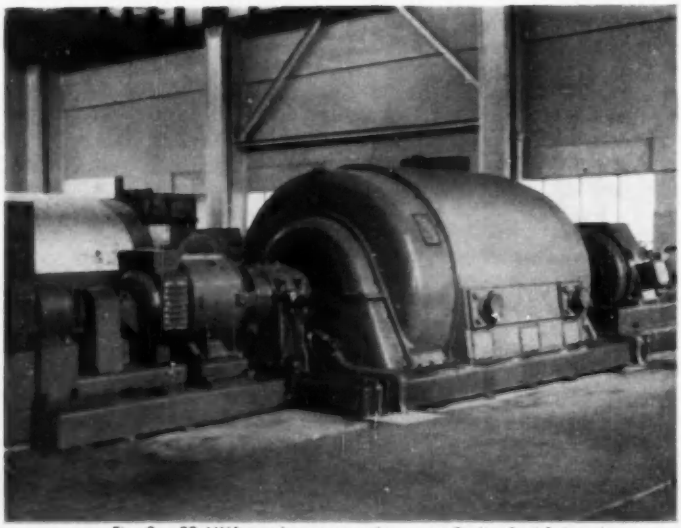


Fig. 2.—20 MVA synchronous condenser at Carlingford Substation.

The synchronous condensers are air-cooled machines nominally rated at 20 000 kVA at 11 kV and are connected to tertiary windings on the main 132 kV transformers. At one end each machine is coupled to main and pilot exciters and at the other end to a synchronous induction pony motor and exciter (fig. 2).

The machines, which comply with the Australian Standard Specification No. C.26, run at 1000 rev/min and are designed to operate over the following range:

When running over-excited, 21·8 MVA at 12 kV.

When running under-excited, 10 MVA at 10 kV.

OPERATION.

Large synchronous condensers are usually started by means of a pony motor or by applying a reduced voltage

to the machine terminals. In this instance a low-voltage synchronous induction pony motor is used because it is economical in power, causes least disturbance to the system when running up to speed and it simplifies synchronizing.

The mechanical displacement in the coupling between the pony motor and the synchronous condenser is arranged to correspond to the phase displacement between the low and high voltage supplies at the motor and condenser terminals. Hence the condenser is brought automatically into the correct phase relationship for synchronizing when the set is up to speed, and the surge when closing the main circuit breaker is small.

A pilot exciter is embodied in the excitation system to ensure rapid response under load fluctuations and to maintain stability when running the condenser under-excited. A differential field winding in the main exciter field system neutralizes the residual field magnetism and enables the automatic voltage regulator to force down excitation quickly. To suit the low-voltage heavy-current characteristics of the excitation circuit of the pony motor, a separate direct-coupled exciter is employed.

The alternative method of using the exciter serving the synchronous condenser would involve undesirable compromises in design owing to dissimilar requirements, and would increase the difficulty of maintaining stability when running under-excited.

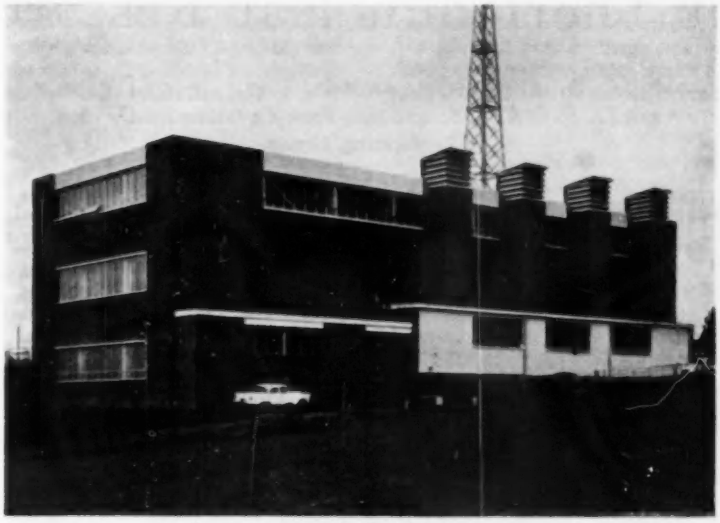


Fig. 4.—Exterior of Carlingford Substation.

CONSTRUCTION.

The stator frame of each machine is of fabricated construction, and a winding of the two-layer type is employed. The rotor body (fig. 3) is a steel casting with integral poles, and the rotor coils are formed with every third turn projecting beyond the other two to increase the effective surface area exposed to the stream of cooling air. The bearings are cast-iron bushes lined with white metal, and are supplied with oil from a high-pressure jacking system and a low-pressure lubrication system. The high-pressure system, which comes into operation when the machine starts from rest, consists of a motor driving two independent oil pumps, each developing a pressure of 500 lb/in^2 and serving one of the main bearings.

Each synchronous condenser is self-ventilated and is provided with axial-flow fans designed to induce an air flow of 30 000 ft^3/min. The hot air is exhausted underneath the machine shell and is then conveyed through ducts to louvred vents at the top of the four brick turrets which form a prominent architectural feature of the substation (fig. 4).

Comprehensive interlocking and safety features are incorporated to ensure that the machines will operate safely in an unattended substation and the protective equipment includes biased differential protection, together with relays which afford protection against stalling, overloads, high exhaust air temperature, high bearing temperature and low oil pressure.

COMMISSIONING.

Delivery and commissioning was programmed to meet the requirements of the Electricity Commission which, following its establishment in 1950, was faced with formidable problems of organization arising from the amalgamation of independent authorities. The first machine was placed in service in 1957 followed by others in 1958 and 1959.

ACKNOWLEDGEMENT

Acknowledgement is made to the Electricity Commission of New South Wales for permission to publish the foregoing information and illustrations.

Charging of High-Voltage Capacitors for Thermonuclear Research

By A. D. APPLETON, B.Sc.(Eng.), Atomic Energy Division,
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Engineering Group.

Many experiments on controlled thermonuclear reactions require high-voltage capacitors to achieve a high rate of energy input to the apparatus. The G.E.C. has developed, specifically for this application, a capacitor charging unit which produces a constant charging current by the use of a saturable reactor. The equipment, the operation of which is described, is inherently safe against short-circuits in the load and includes a feedback control system to give optimum working conditions. Several capacitor banks can be charged to different voltages under fully automatic cyclic operation in a very stable manner. Some of the units of ratings up to 100 kV that have been supplied to the United Kingdom Atomic Energy Authority are illustrated.

CAPACITORS IN THERMONUCLEAR EXPERIMENTS.

EXPERIMENTS are being carried out in many countries with the ultimate aim of obtaining electricity from controlled thermonuclear reactions. In common with the requirements of many other nuclear experiments, the equipment necessary is usually more typical of large engineering projects than of the older type of physics laboratory. Energy must be supplied to the ionized gas at an exceedingly high rate, using currents of the order of 10^5 or 10^6 amperes and potentials of up to 10^5 volts, and it is therefore inevitable that the experimental equipment should become rather substantial.

The energy may be transferred from a store to the gas in a number of ways; it may be fed into coils to produce a rapidly changing magnetic field which will compress an ionized gas, it may be fed directly into the gas by means of electrodes, or indirectly by way of the magnetizing flux of a transformer. In a toroidal-pinch discharge, an elegant approach to the fusion problem, the energy is fed into a primary winding very closely coupled to the gas discharge which forms the secondary circuit of the resultant transformer. It is necessary for the gas discharge current to grow very rapidly, form into a thin skin, and very quickly leave the walls of the containing vessel. If these requirements are not met there is no hope of heating the gas to the required temperature for the necessary time, because instabilities, impurities, and energy-loss mechanisms will extinguish the discharge.

The only store which will release its energy rapidly enough is a low-inductance capacitor of a sufficiently high voltage to give the required rate of current rise. To some extent the capacitor voltage is arbitrary, because the voltage per turn of the primary winding may be reduced by having more than one turn or increased by using a number of capacitors in series. In practice, though, there are difficulties in trying to carry the latter too far; it leads to increasing complexity and cost of construction, and increasing losses in external circuits.

The tendency, therefore, is to use capacitors at higher and higher voltages, but it seems likely that insulation and switching problems will impose a limit of about 100 kV for some time to come.

Apart from the energy requirements of the main discharge circuit it is often convenient, and sometimes necessary, to use capacitors for other functions. These are:

(*a*) To produce an axial magnetic field;
(*b*) To preheat the gas;
(*c*) To produce a reverse axial magnetic field.

A necessary feature of all pinch discharges is that an axial magnetic field (B_Z) must exist before the main current is present; thus when the main discharge-current channel pinches to a smaller diameter it compresses the axial magnetic field, which produces an internal stabilizing magnetic pressure. The time taken to produce the axial field is unimportant, except perhaps from considerations of coil design, and therefore the energy store may be of any form. Batteries are sometimes used for this purpose. However, low-voltage capacitors (a few kV) are very convenient, requiring no maintenance; and as they are also easily controlled, they are often used in this application.

It is often necessary to have the gas in the discharge vessel in as fully ionized a state as possible before the main discharge circuit is triggered. A satisfactory way of doing this is to pass a smaller current just before the main discharge, and capacitors are again the most convenient means of storing the necessary energy. The discharge voltage per turn necessary for the preheat coil is of course lower than that required for the main coil, and therefore lower-voltage capacitors may be used.

One of the principal difficulties in high-current pinch discharges is that, even with the initial B_Z field, the discharge is still unstable after a relatively short time. Theoretical studies have indicated that the situation may be improved if another axial magnetic field is produced in the direction opposite to that trapped inside the pinch. This reverse magnetic field (B_{ZR}) is required immediately outside the main current channel, and is therefore at right angles to the magnetic field (B_θ) produced by the main discharge current. Stability may be improved if a calculated relationship of the magnitudes of B_Z in one direction, B_θ at 90°, and B_{ZR} at 180°, is made to exist. This relationship requires the reverse magnetic field to be set up in the same order of time as the main current; it is therefore necessary to use capacitors also for this purpose.

If all the above functions are built into one experiment it may be required to have up to four capacitor banks, conceivably at four different voltages and probably required to work on automatic cyclic operation.

CHARGING OF CAPACITORS.

A capacitor may be charged simply by applying a voltage through a resistor, and for many applications this is perfectly satisfactory. The method is most uneconomical, however, in the rating of equipment, very crude in control, and quite impracticable when considering large banks of high-voltage capacitors.

The most economical method of charging a capacitor is to allow the voltage to rise linearly so that the charging current is constant. This may be achieved:

(*a*) By controlling the voltage by means of an induction regulator and allowing the current to be the dependent variable;

(*b*) By controlling the current by means of a saturable reactor, with the capacitor voltage as the dependent variable.

The equipment to be described is based on the second of these alternatives, that is constant-current control, which is shown to have many advantages over the voltage-control method. This control system is very adaptable to the particular requirements of the experiments for thermonuclear research; for example a single unit may be made to charge several capacitor banks to different voltages under fully automatic cyclic operation in a very simple manner. One of the most valuable features of the equipment is that the output of the rectifiers may be short-circuited without the risk of any damage.

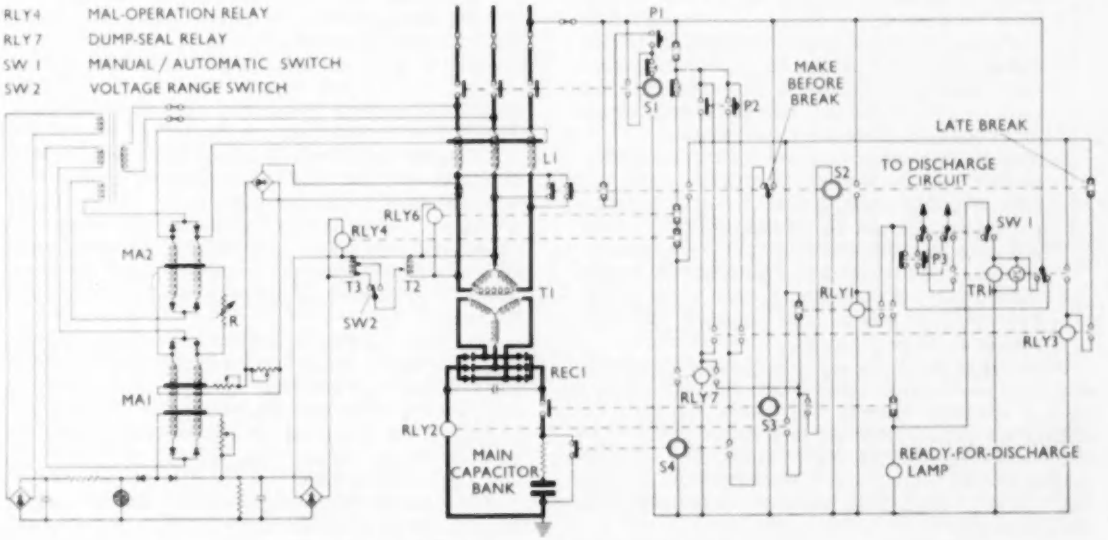

Fig. 1.—Simplified circuit diagram of basic charging unit.

OPERATION OF THE CHARGING UNIT.

The basic principle of the charging system is to maintain a constant charging current from approximately the start of the charging cycle until the voltage on the capacitor is within a few per cent of its final value. The salient features of the design are:

1. The use of a saturable reactor, which enables the charging current to be established very rapidly. The time to reset the equipment is also much shorter than that required with an induction-regulator control system, where a run-down time of several seconds has to be allowed at the end of each charging cycle.
2. The application of the known constant-current characteristics of the d.c.-controlled saturable reactor to produce a constant charging current and hence a constant rate of charge.

3. The use of a positive feedback winding which is necessary to enable the charging current to reach its maximum value in a minimum time consistent with stability. If positive feedback is not applied, the regulation of the transformer-rectifier unit over-damps the system.
4. The inclusion of a charging switch:
   (*a*) To give zero output when charging is not required;
   (*b*) To deflux the transformer during the capacitor-discharge period;
   (*c*) To provide a means of giving an exact start to the charging period.
   However, in order to limit the reactive current taken from the supply before the charging switch is opened, the circuit may be arranged so that the control reactor is passing its minimum current until opening of the switch, afterwards building up to its preset value at a rate determined by the time constants of the control amplifiers.
5. The use of a closed-loop voltage-control circuit, which works for most of the charging cycle in a fully saturated state so that during this period a charging rate can be set independently of the action of the closed-loop circuit. The voltage-control circuit comes into operation only during the final part of the charging cycle to cut off the full charging current and establish the final voltage at the preset level.

Referring to fig. 1, the equipment consists basically of a main transformer-rectifier unit, *T*1, *REC*1, and a control saturable reactor, *L*1, which regulates the transformer primary current to a preset value. The main control reactor *L*1 is itself controlled by magnetic amplifiers, *MA*1, *MA*2, which also cut off the charging current via *L*1 when the required capacitor voltage has been obtained.

Current Setting.

The magnetic amplifier *MA*1 is arranged to run near to full output so that its current is controlled during charging by the circuit resistance. The current-setting resistor, *R*, is in a low-power circuit, so that a small potentiometer is suitable for controlling charging currents of up to 500 A, 3-phase, and the current control may therefore be mounted on a convenient remote panel. Charging currents in the range of 5% to 100% of the nominal rated output current are possible.

Voltage Setting.

The primary voltage of the transformer, which rises with the voltage of the capacitors, is compared with the fixed reference voltage of a neon tube. When the primary voltage exceeds that of the neon tube, a signal is produced in *MA*1 which reduces its output. This in turn cuts down the output of *MA*2 which reduces the charging current through *L*1, the main control reactor. As the voltage across the neon tube is constant, the voltage derived from the transformer primary will always be the same at the point of cut-off. Therefore a variable-ratio transformer, *T*2, is interposed between the comparator circuit and the transformer primary, enabling the charging current to be cut off at any required capacitor voltage.

The variable-ratio transformer operates in the reverse way to normal, which means that a non-linear scale has to be used. In order to prevent this scale from being unduly cramped at the high-voltage end a tapped transformer, *T*3, with a selector switch is used to give a dual range setting.

Operating Sequence.

Discharge of the capacitor bank is controlled by a separate circuit, which operates a trigger spark-gap and thence the main spark-gaps linking the capacitors with the discharge coils. When the equipment is under manual control, indication that the capacitors are fully charged is given by a lamp, and discharge is then initiated by a pushbutton; with automatic cyclic operation, discharge is initiated by a signal obtained directly from the charging circuit.

According to the type of experiment for which the capacitors are required, it is sometimes necessary to short-circuit the capacitor through a resistor after a discharge. This is to guard against the possibility of a reversed polarity of the capacitors due to ringing in the inductive load. The typical operating sequence to be described includes such dumping as well as automatic discharge.

The main charging equipment is fed from a 3-phase electrical supply through a mains contactor, *S*1, which has overload trips and back-up fuses. The contactor may have a number of auxiliary interlocks (for example, as part of the experimental-area earthing system) in addition to an interlock to prevent closure if the charging switch is open.

The required charging current and capacitor voltage are selected as described above. Then, following the operation of the start button, *P*2, the dump-seal relay picks up, the dump switch, *S*4, is opened, the high-voltage isolating switch, *S*3, is closed, the charging switch, *S*2, opens, and charging commences. As soon as the charging current is established, a current-sensitive relay, *RLY*2, picks up and holds in the supply to the charging switch, taking over from the time-delayed relay, *RLY*1.

When charging is completed, the voltage-sensitive circuit cuts off the current as already described and the relay *RLY*2 drops out, allowing the charging switch to close and the high-voltage isolating switch to open. The relay *RLY*1 is sealed in via the discharge push-button, *P*3, and the ' ready for discharge ' lamp is lit; when the discharge button is pressed, *RLY*1 is reset. As the charging switch closes, the dump-seal relay is de-energized, but this does not instantaneously de-energize the dump switch, because the drop-off of the relay is delayed by a variable preset time to allow for capacitor discharge to take place.

Under automatic conditions the timer, *TR*1, is started when the ready-for-discharge condition is reached. This then resets relay *RLY*1, and closes the discharge circuit for a preset period. Following this, the timer picks up the relay *RLY*3, which seals itself

in via a normally closed late-break contact on the charging switch. *RLY*3 has a contact in parallel with the start pushbutton so that the dump seal relay is re-energized and the charging sequence recommences. The time setting of *TR*1 must be longer than that of the dump-seal relay in order that dumping may take place before the equipment can restart.

The control circuitry may easily be arranged to charge several capacitor banks in sequence, as indicated in fig. 2. The additional equipment required is a variable-ratio transformer and current-setting potentiometer for each bank, and a changeover relay. Each bank also requires, of course, a high-voltage isolating switch, and these are electrically and mechanically interlocked so that only one can be closed at a time. Additional protection may be provided by high-voltage fuses, as indicated, and by the use of spark gaps to earth.

Protection in the charging unit itself is provided by means of a sensitive overvoltage relay, *RLY*6, which closes the charging switch if the voltage rises above a safe level for the capacitors owing to a wrong setting of the transformer or a failure of the neon reference voltage. A mal-operation relay is provided to close the charging switch in the event of operation of the voltage range switch during charging. In addition there is the normal protection provided by fuses and contactor overload trips. Protection of the main rectifiers against external events will be described later.

The circuits of fig. 1 and 2 are intended only as guides to the control system; they lack much detail in the feedback loops and do not show the metering equipment or indicating lamps.

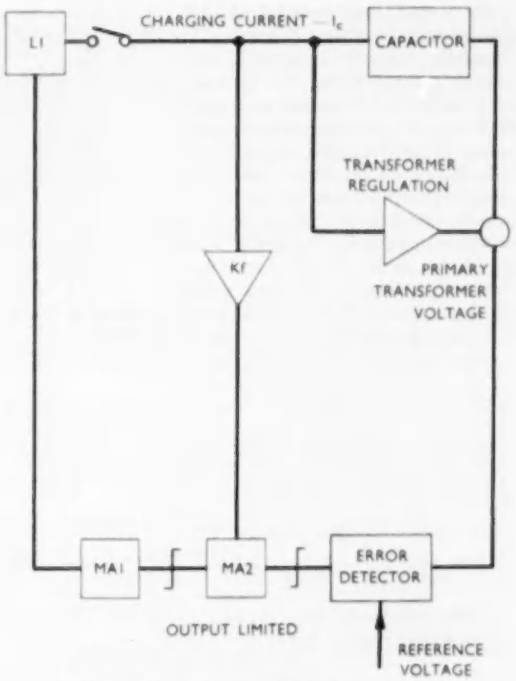

Fig. 3.—Block diagram of the control circuit.

STABILITY OF THE CONTROL SYSTEM.

The control system, shown schematically in fig. 3, is inherently stable because of the damping effect produced by the transformer-rectifier regulation. This means, however, that a relatively long time is needed before the final capacitor voltage is actually reached. To overcome this, positive feedback, *Kf*, is used to accentuate the cut-off of charging current. This, in effect, is counteracting the transformer-rectifier regulation, and making the system less stable; consequently there is a limit to the amount of feedback that may be introduced.

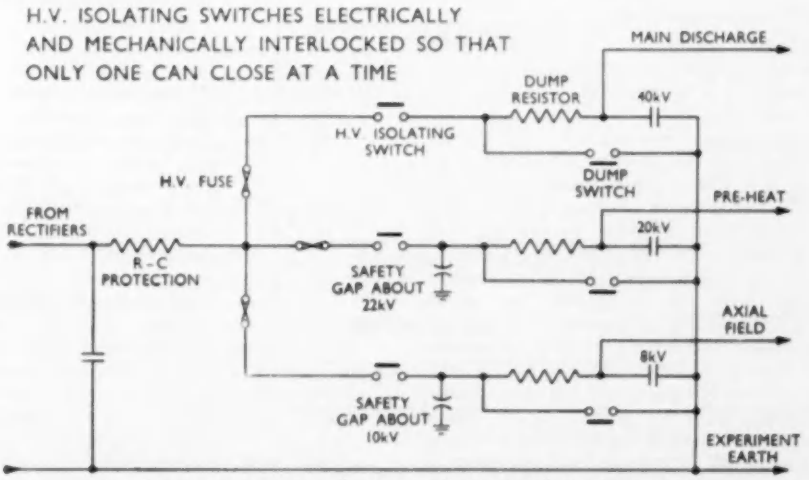

Fig. 2.—Control circuit to charge several capacitor banks in sequence.

The transformer primary voltage is allowed to overshoot the value corresponding to the capacitor voltage setting on no load. If too much positive feedback is used, the capacitor voltage also overshoots the set value. Therefore, the optimum value of positive feedback is that which produces a sharp cut-off of charging current, but which does not allow overshooting of the capacitor voltage to take place.

A stability study has been made on an analogue computer to determine the optimum settings for the feed-back loop. Fig. 4 shows some results obtained with different values of feedback.

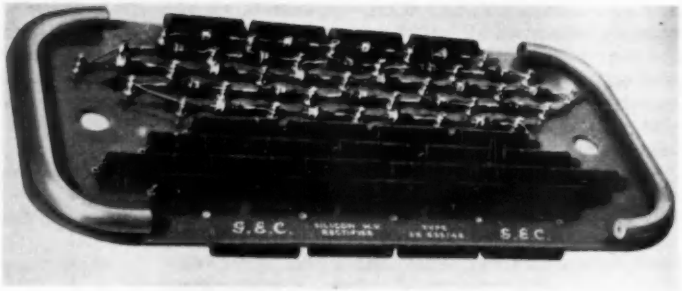

Fig. 5.—Silicon-rectifier wafer.

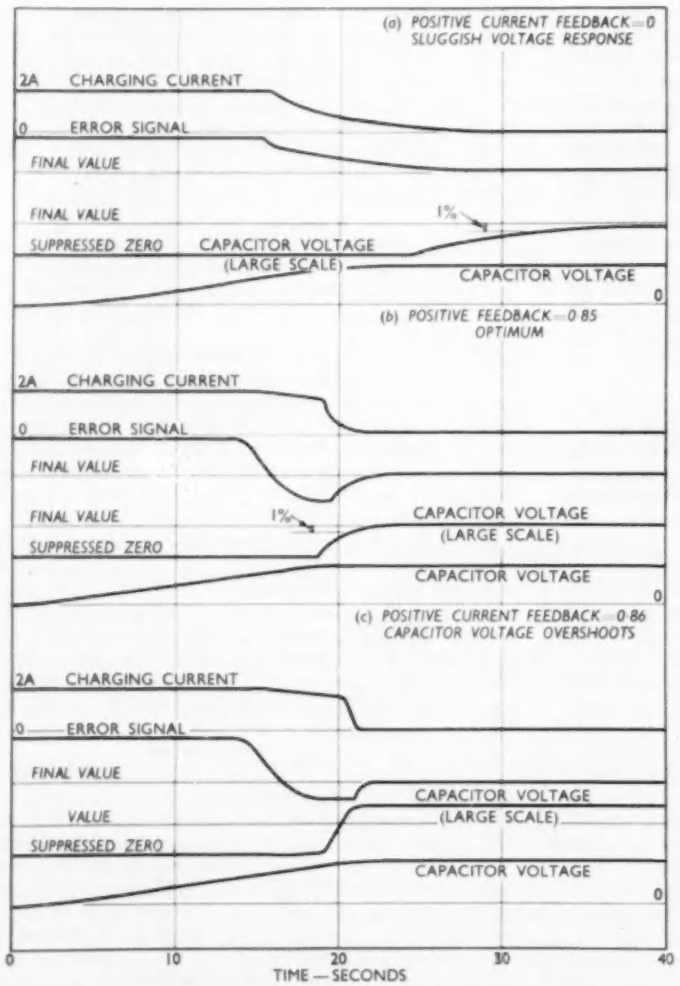

Fig. 4.—Computer curves showing the effects of positive feed-back on the approach to full charge of the capacitor.

HIGH-VOLTAGE RECTIFIER.

Silicon Diodes.

Silicon rectifiers are smaller, lighter, and more economical to operate in high-voltage applications than any other type of rectifier. The G.E.C. high-voltage silicon rectifiers to be described were designed for capacitive or resistive loads such as electrostatic precipitators and X-ray apparatus, and are thus well suited to capacitor charging. Owing to the small size of the diode elements the dimensions of the rectifier stack are practically limited by the breakdown properties of the insulating medium alone. The rectifiers may be mounted in air or immersed in oil; in this application, for reasons of compactness and general simplification, the rectifiers are mounted in the oil of the transformer.

The basic element of the stack is a rectifier wafer, an example of which is shown in fig. 5, consisting of a chain of silicon diodes assembled on an insulating panel. The edges of the panel are fitted with round guard rails to prevent high dielectric-stress concentrations and to reduce stray capacitance effects.

Stray capacitance becomes of paramount importance with long diode chains when steep voltage surges are present, since the diode-to-earth capacitances and the junction capacitances combine to form a ladder network, with the result that a voltage surge is initially divided between the first few elements and the earth strays. This difficulty is overcome by connecting a chain of capacitors in parallel with the diodes, effectively equalizing any surge distribution and limiting the maximum

peak inverse voltage to a safe value for any diode in the chain. This forced surge-division also overcomes the danger arising from unequal recovery times of the individual diodes. In the absence of the correction capacitors the rising reverse voltage following the conducting period would be borne by that diode of the chain which recovered first from the hole-storage effect. The efficiency of the forced surge-division depends, however, on maintaining the earth strays at a low level, and this is fully considered in designing the mounting and clearances of the wafers. The shunt capacitors constitute a small additional load on the transformer and add to the output ripple, but this effect is negligible at normal power frequencies.

The typical rectifier wafer shown in fig. 5 consists of an assembly of 48 silicon diodes in series, individually protected by shunt capacitors of 0·02 μF each, and mounted on an insulating panel measuring 12 in. × 6 in. The performance of the wafer is shown in the table. Efficiency of the rectifiers is between 96 and 98%, and there is no measurable change of characteristics due to ageing; under correct operating conditions the lifetime may be considered infinite.

The G.E.C. silicon diodes have been thoroughly tried in many applications, and the high-voltage wafer has been subjected to exhaustive laboratory tests. In general, the operating conditions of a wafer would be made conservatively below the maximum rating; for example the maximum peak inverse voltage that would be applied to the wafer described above would be about 14 kV.

TABLE 1.

PERFORMANCE FIGURES FOR THE G.E.C. RECTIFIER WAFER TYPE SX 633/48.

Maximum ratings:	
Peak reverse voltage, absolute value ...	17 kV
D.C. output, any load, oil-cooled ...	750 mA at 70° C oil temp. 500 mA at 100° C oil temp.
D.C. output, any load, air-cooled ...	750 mA at 45° C ambient temp. 500 mA at 70° C ambient temp.
Surge current (10 millisecond duration)*	10 A
Storage temperature limits	−40° C to 120° C
Characteristics (typical values):	
Reverse direct current at 17 kV ...	5 μA at 100° C
Forward voltage drop at 1 A d.c. ...	50 V at 25° C
Power dissipation (proportional to forward current)	36 W at 0·75 A (25° C)
Total shunt capacitance	420 pF

* Higher currents may be tolerated for shorter times.

Selenium Rectifiers.

Selenium rectifiers are appreciably cheaper than silicon rectifiers at the present time, but their efficiency is much lower. The selenium rectifier is also more robust than silicon in the case of transient overloads. The choice between the two rectifiers, although largely a matter of cost, is also dependent upon the type of control equipment employed. This is discussed later.

Rectifier Protection.

There are two conditions under which the rectifier may be subjected to overload currents:

1. A short-circuit of the rectifier output.
2. A reverse potential across the rectifier due to ringing in the capacitor-discharge circuit.

For a short-circuit of the output, the rectifiers are completely protected by the constant-current characteristics of the control saturable reactor. Even if the short-circuit occurs at maximum voltage no damage will be sustained by either a silicon or selenium rectifier.

Tests carried out on a 110 kV unit to determine the overload imposed under short-circuit conditions have shown that the instantaneous overload peak for the worst case is still well within the safety limits of the rectifiers. Fig. 6 shows a typical oscillogram obtained. These tests were carried out at different reactor saturation levels and with different load impedances, and as would be expected those corresponding to full charging current at full output voltage produced the severest transients. The method used was to short-circuit the saturable reactor; in service, where the short-circuit would take place on the output of the rectifiers, further peak limitation would be imposed by the impedance of the transformer-rectifier unit.

For selenium rectifiers, the margin in hand will be greater than for silicon. However, in either case an inherently safe protection is provided by the use of saturable-reactor control, and no additional short-circuit protection is required. For an induction-regulator control system, using silicon rectifiers, protection against a short-circuit is a formidable problem. Any solution, such as interposing resistance between the transformer secondary and the rectifier bridge, must involve an increase of rating and some of the advantage of using silicon is lost.

A reverse potential across the rectifier cannot occur if a high-voltage isolating switch is used, unless the capacitor spark-gap operates prematurely. In some cases, however, it is convenient to cut out the isolating switch, and therefore some form of protection is required. This may be conveniently provided by a resistance-capacitance network as shown in fig. 1; the time constant of this network is made long in comparison with the decay time of the ringing discharge, so that the potential across the rectifier never changes sign. As a further protection, a reverse-voltage relay is sometimes used to prevent the closure of the high-voltage isolating switch on to a capacitor bank holding

a reverse charge, but this is not necessary where automatic dumping is employed.

RATING AND TYPE OF EQUIPMENT.

The voltage and size of a capacitor bank are determined by the requirements of the experiment. The other major parameter affecting the rating of the equipment is the charging time. As a starting point, the specification may lay down the required frequency of discharges—a decision which may perhaps be dominated by the number of conditioning discharges which the experiment requires—and the first objective is to use as much as possible of the time between discharges as actual charging time. This is because the kVA rating of the equipment is approximately CV^2/t, where t is the charging time. An important advantage of the saturable reactor is that the time between discharges can be utilized to the full.

The rating of the equipment is reduced by using a silicon rectifier, because the forward voltage-drops and reverse-current characteristics are much more favourable than for selenium; the transformer secondary voltage and primary current are reduced, and therefore a smaller control reactor may be used. However, for smaller units this saving is outweighed by the higher cost of silicon, and selenium rectifiers are generally used.

A factor affecting the size of the saturable reactor, and hence the maximum kVA demand on the power supply, is the linearity of the charging current. As shown in fig. 7, the reactor tends to lose its ideal constant-current characteristic as the voltage across it falls, and if it is required to have constant current over as much of the charging cycle as possible it is necessary to ensure that the reactor does not work near the bottom bend of its characteristic. As the capacitor becomes charged, the voltage across the control reactor falls. If it is not allowed to fall into the non-linear part of the characteristic, the transformer primary voltage at maximum capacitor voltage and charging current is necessarily lower than it could be, and the primary current and reactor rating are correspondingly higher. On the other hand, allowing a 10% increase in transformer primary voltage will result in a similar reduction in primary current, kVA demand, and kVA rating of the reactor, with the disadvantage of a slightly prolonged charging time at the highest capacitor voltages.

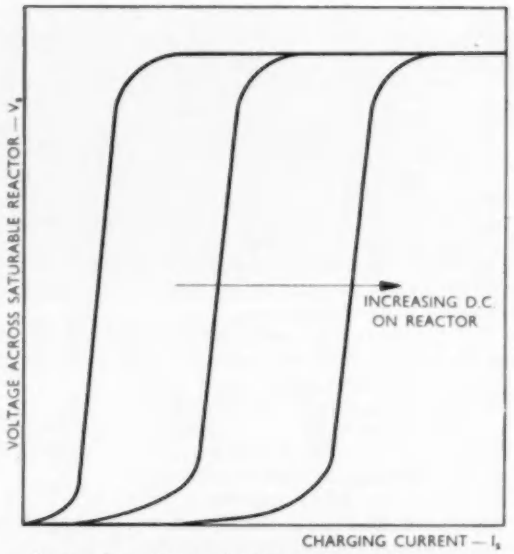

Fig. 7.—Characteristics for the control saturable reactor.

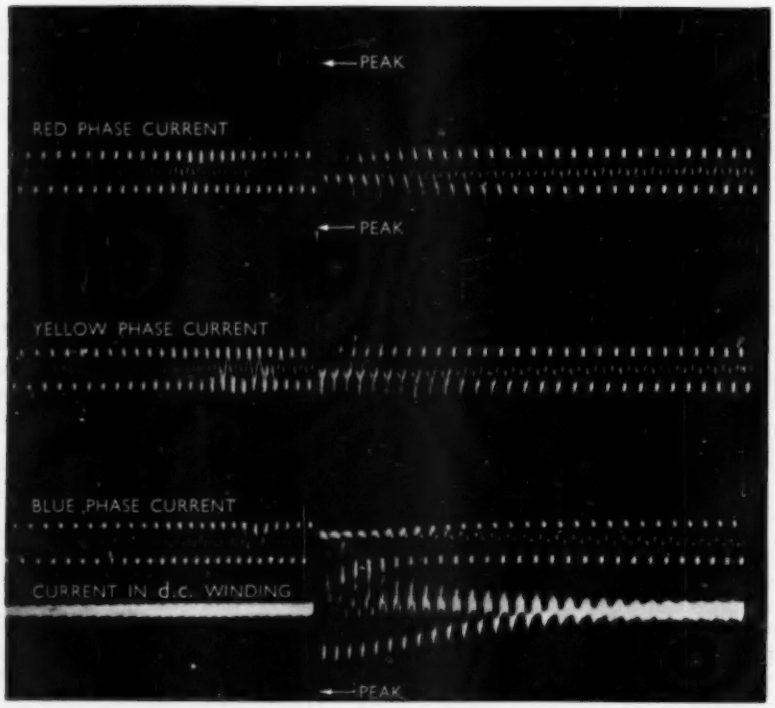

Fig. 6.—Oscillogram illustrating short-circuit tests on a 3-phase 22 kVA saturable reactor. (30 A r.m.s., 300 A peak short-circuit. Load before short-circuit equivalent to charging a capacitor at full voltage.)

For smaller units it is convenient to set the charging current flowing with the charging switch closed. In larger units, because of the reactive kVA demand when the charging switch is closed, the charging current is kept at its minimum level until charging actually commences, when the current will reach its pre-set value in less than one second.

Advantages of Saturable Reactors.

As has been shown, silicon rectifiers have advantages over selenium, particularly when the unit is sufficiently large for the reduced rating and cooling costs to outweigh the difference in the cost of rectifiers. The size at which this occurs is smaller for a saturable-reactor system than for an induction-regulator system, when due consideration is given to the protection of the rectifiers against short-circuits.

Other advantages of using a saturable-reactor scheme rather than an induction regulator are:

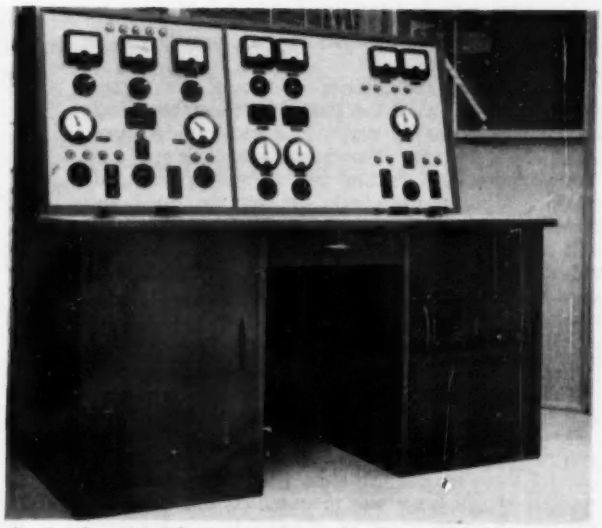

Fig. 9.—Control desk for charging units used in fast-toroidal-pinch equipment.

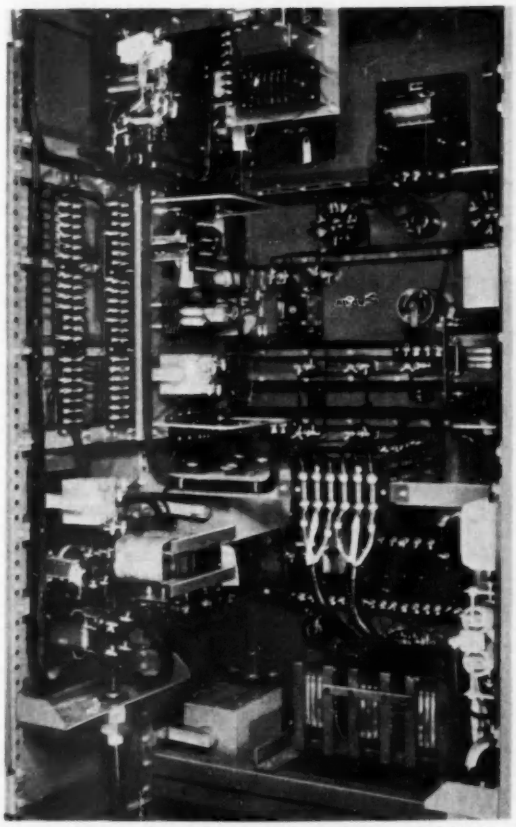

Fig. 8.—Interior of one of the control cubicles for a 100 kV 0·4 A charging unit.

(*a*) Great reliability, with no moving parts to require maintenance;
(*b*) No run-down time between charging cycles—a factor which reflects directly on equipment rating;
(*c*) Inherent protection of rectifiers against short-circuits;
(*d*) Very simple controls.

A disadvantage is an increase in the maximum kVA demand, but this increase may be kept quite marginal by the methods given above.

EQUIPMENT SUPPLIED TO U.K.A.E.A.

A number of 20 kV, 40 kV, and 100 kV charging units have been supplied to the United Kingdom Atomic Energy Authority at Harwell for controlled thermonuclear experiments. Some of these units are intended for charging only one capacitor bank, but others are designed to charge two and three capacitor banks to different voltages under automatic cyclic operation.

A unit usually consists of three items:

1. A control cubicle which contains the magnetic amplifiers, contactors, and relays for sequencing the operation. The cubicle may contain the control pushbuttons, with current and voltage selectors, but it is sometimes required to mount these controls on a separate control desk.
2. A saturable reactor housed in its own case separate from the control cubicle. (For small units the saturable reactor is mounted in the control cubicle.)
3. A transformer with an oil-immersed rectifier, mounted in a common tank with barriers between them; the high-voltage connexions between transformer and rectifier are made under oil in the tank, and both ends of the rectifier are fully

insulated and brought out on high-voltage bushings so that the capacitor may be charged to either polarity.

Fig. 8 shows the interior of one of the control cubicles for 100 kV 0·4 A charging equipment which has been supplied for use with a fast toroidal pinch using shock heating. The capacitor bank is split into five sections, each feeding two flanges of the torus (making it possible to obtain 10^6 volts per turn), and the charging equipment is in five separate units. This will enable it also to be used for several independent experiments at a later date. Each of the five cubicles may be operated individually, or remotely from the control desk shown in fig. 9. Any number of the units can also be ganged together and operated automatically from the desk, only one voltage control then being required. Selector switches allow the charging current and voltage of any individual unit to be observed.

Two additional capacitor banks are required for this experiment, for pre-heat and axial magnetic field, and both of these are charged from a 20 kV 2 A unit, the controls of which are also mounted on this desk. In addition, a space has been allowed to accommodate controls for a reverse axial magnetic field should this be required at a later date; additional terminals giving the necessary access to the control circuit have been provided on the 100 kV equipment to cater for such a requirement.

Some of the transformer-rectifier units for this experiment are shown in fig. 10; these are installed just outside the experimental area, and the high-voltage leads pass through the wall to a switch platform. The transformers are mounted in fire-trap tanks to meet the Harwell safety requirements.

The control cubicle shown in fig. 11 is for a 40 kV 1 A unit, which is intended for use with a number of experiments including a straight-tube discharge with reverse axial magnetic field. It can be seen from the mimic diagram that it is designed to charge three separate capacitor banks, and clear indication is given of which banks are charging and which banks are charged. Operation is manual or completely automatic, as required.

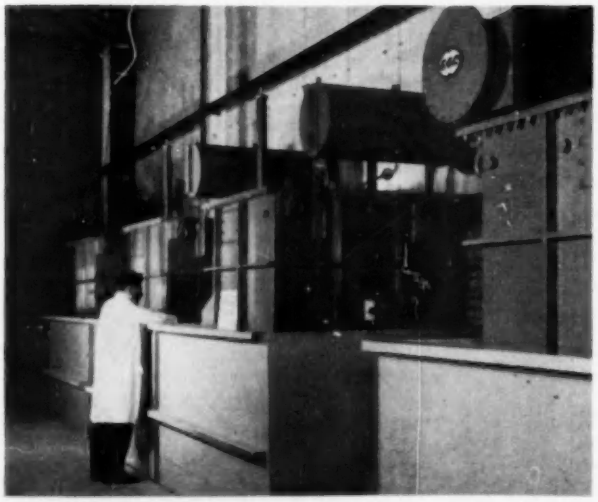

Fig. 10.—Some of the transformer-rectifier units for the fast-toroidal-pinch experiment.

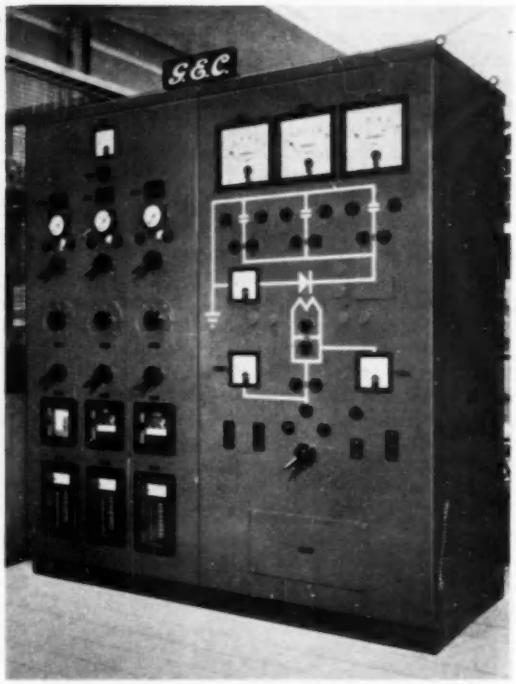

Fig. 11.—Control cubicle for a 40 kV 1 A charging unit.

A 40 kV 1A charging unit has also been supplied to Harwell for a large straight-tube experiment. As supplied it was intended only for charging one bank, although the additional terminals for circuit access had been provided. On site, the equipment was modified so that it would charge an additional 8 kV capacitor bank for an axial magnetic field, under automatic cyclic operation. This modification also included the provision of facilities for automatic discharge and safety dumping after each shot.

ACKNOWLEDGEMENTS.

Acknowledgement is due to the U.K.A.E.A., and in particular Maj. P. Worsnop and Mr. E. Bratt of the C.T.R. Division, A.E.R.E., Harwell, for their co-operation and permission to publish photographs of the installed equipment.

Single-Sideband Communication

By A. CORMACK, B.Sc., A.M.I.E.E., Research Laboratories.

The G.E.C. is developing a complete single-sideband h.f. receiving system, comprising a comprehensive receiver and a frequency synthesizer. The receiver is designed for all classes of amplitude-modulated signal reception. This article reviews the s.s.b. communication system and some design considerations of the receiving equipment.

INTRODUCTION.

FROM the earliest days of radio communication it has been customary to transmit information by modulating a carrier frequency. The carrier provides the means of translating the information to any desired part of the frequency spectrum and also provides a ready means of identification for each signal.

When a carrier is modulated in frequency, phase, or amplitude, the result of the process is a composite signal. If analysed on a frequency basis, this composite signal will be found to contain the carrier frequency, a group of frequencies lower than the carrier frequency, and a group of higher frequency than the carrier. The first group is known as the lower sideband, and the second as the upper sideband. The upper and lower sidebands both contain the same information (the modulation information) and therefore one of them is redundant. The carrier-frequency component contains no modulation information and merely serves to identify the signal. If the recipient knows the transmission frequency, that is, the carrier frequency, then the carrier component adds no information and it too may be regarded as redundant.

When, therefore, after a normal modulation process the carrier component and one sideband are removed before transmission, the remaining sideband will contain all the signal information. This form of signal is known as a single-sideband suppressed-carrier transmission.

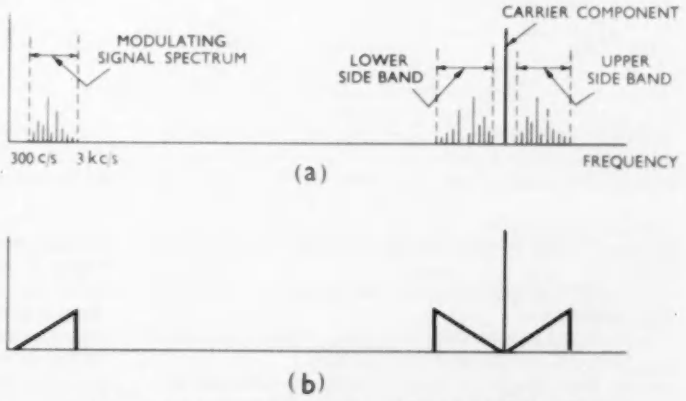

Fig. 1.—(a) Frequency spectrum of amplitude-modulated carrier. (b) Diagrammatic representation of (a).

THE SINGLE-SIDEBAND AMPLITUDE-MODULATED SIGNAL.

In the h.f. band, that is at frequencies below about 30 Mc/s, amplitude modulation is the form usually employed. A telephone-quality speech signal will contain audio frequencies in the range 300 c/s to 3 kc/s and amplitude modulation of a carrier at frequency f_1 by this signal will produce the frequency spectrum shown in fig. 1. Suppression of one sideband will then reduce the frequency spectrum to one half the width.

If mutual interference between signals is to be avoided they must occupy separate parts of the frequency spectrum. The broadcast and h.f. bands are already overcrowded and the saving of bandwidth achieved by the use of s.s.b. techniques is of considerable value.

Consideration of power consumption shows that s.s.b. offers another very real advantage. A normal double-sideband amplitude-modulated signal when fully modulated contains half the total power in the carrier component, and only one quarter in each sideband. For communication purposes 75% of the available power is therefore used in providing unnecessary components. For a given available transmitter power the s.s.b. technique will provide a better service, either in increased signal strength giving clearer reception, or in increasing the range of communication. Alternatively the same standard of communication may be maintained with s.s.b. as with d.s.b. operation, with only one quarter the transmitted power.

A reduction in the power to be transmitted may result in a saving both in capital cost of the transmitter and in operating cost. For airborne operation two aspects are of importance. Firstly the small concealed aerials which have to be employed are restricted in the power that they will handle, particularly at high altitudes. It is therefore important, when maximum possible communication range is required, that the power which can be transmitted is all useful power. Secondly improved transmitter efficiency can be reflected in smaller and lighter equipment, and in a saving in the power required from the aircraft generators.

The main advantages of s.s.b. operation can be summarized as:

1. A saving in bandwidth, giving more available space for communication channels.
2. A four to one improvement in transmitter efficiency, meaning smaller, lighter equipment or improved reception.

The chief disadvantage is the complexity of the receiver required.

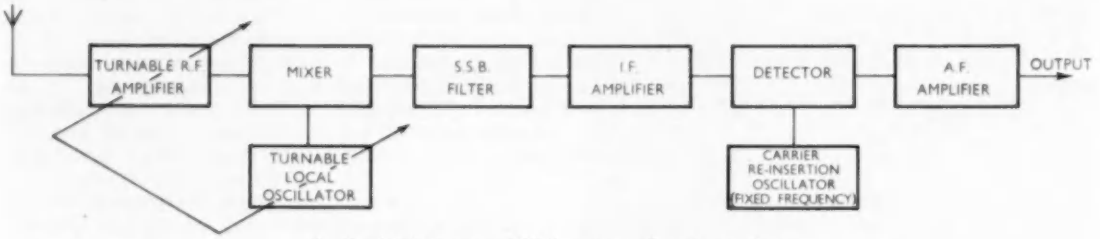

Fig. 2.—Block diagram of S.S.B. suppressed-carrier receiver.

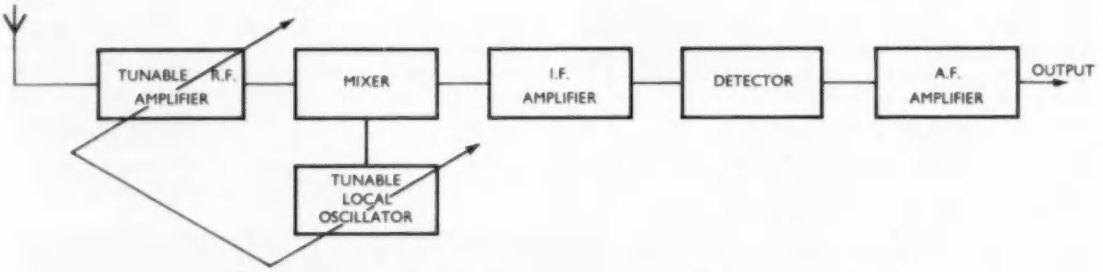

Fig. 3.—Block diagram of d.s.b. superheterodyne receiver.

GENERAL PRINCIPLES OF THE S.S.B. RECEIVER.

Fig. 2 shows the essential block schematic of an s.s.b. receiver. For comparison fig. 3 shows the block schematic of a d.s.b. superheterodyne receiver. The main difference between the two units is in the detection process. D.s.b. detection is usually carried out by a simple diode circuit. This accepts both sidebands and the carrier and gives at its output some r.f. components and the a.f. signal. The r.f. components are simply removed by a filter, and the a.f. output passes on for further amplification and to the loudspeaker. The detection process operates satisfactorily so long as the relative phases and the relative amplitudes of the various frequency components are substantially as transmitted. The operation is reasonably independent of the frequency of the carrier applied to the detector.

To detect an s.s.b. signal it is necessary to recombine the sideband with an oscillation positioned in frequency so as to replace the original carrier component. This re-inserted carrier, as it is called, beats with the sideband components to reproduce the original audio signal. If a signal appears at the detector stage in the position originally occupied by the suppressed sideband a spurious output will result, and this will interfere with the intelligibility of the wanted sideband. To prevent this happening, an s.s.b. filter is provided (fig. 2) immediately after the first mixing process. This filter is designed to pass only those frequencies within one sideband.

In a more detailed examination of the s.s.b. receiver operation, fig. 4 illustrates the process of frequency translation from the received frequency to the audio output. Frequency f_c represents the original carrier frequency. The incoming signal is tuned as in a conventional superheterodyne receiver and mixed with the local oscillator frequency f_o to produce an intermediate frequency $f_i = f_o - f_c$. The wanted sideband has to be positioned sufficiently accurately to pass

through the s.s.b. filter. This means in practice that f_o has to be correctly tuned to better than ± 100 c/s. The final frequency translation takes place at the detector where a frequency f_i has to be re-inserted.

It has been found in practice that for the reception of speech to be satisfactory the overall error in frequency translation must be kept below 100 c/s. Thus the combined error of f_o and f_i should not exceed 100 c/s. For satisfactory reception of certain encoded signals overall errors of less than 10 c/s have to be maintained.

Provided that transmitter and receiver frequency errors can be maintained below these limits, s.s.b. can be employed with a fully suppressed carrier. If not, some carrier frequency component has to be transmitted, not necessarily continuously, and the receiver provided with automatic frequency control of f_o to align the wanted sideband with the s.s.b. filter and detector.

For s.s.b. suppressed-carrier reception f_o has to be accurately positioned. If the receiver is required for the reception of a number of fixed channels, rather than continuously tunable reception, the local oscillator frequency can be obtained from high-stability quartz crystals. If the requirement is for continuous tuning a frequency synthesizer can be used. A synthesizer provides an output which is tunable, but which at all frequencies has the stability of the single-frequency standard to which it is referred.

Automatic gain control of s.s.b. receivers presents problems when a fully suppressed carrier system is used. In full carrier transmission the amplitude of the transmitted carrier component is independent of the modulation and it therefore provides a convenient indication of signal level at the receiver. Changes in propagation conditions can be countered by an a.g.c. which maintains the level of the carrier at the detector constant. A suppressed-carrier s.s.b. signal varies in magnitude from zero to a maximum value just as the modulating signal varies in amplitude. It is therefore necessary to measure the mean value of the signal and to keep this as nearly constant as possible and so reduce the effects of fading, without at the same time impairing the intelligibility of the information being conveyed.

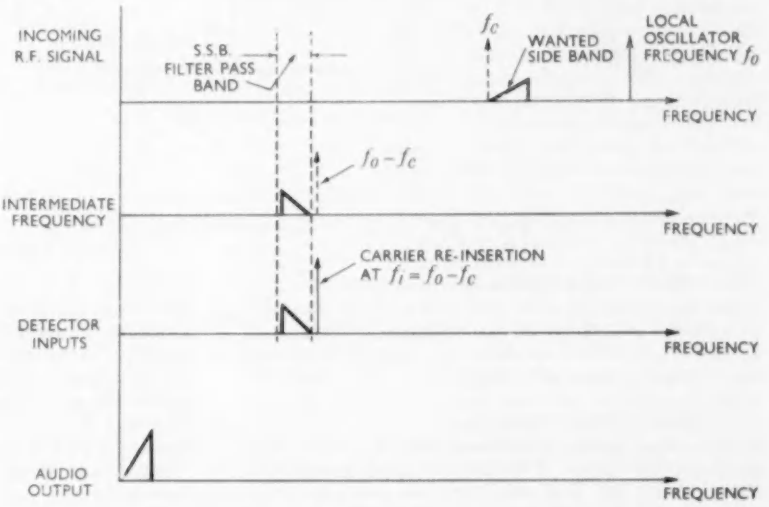

Fig. 4.—Frequency translation diagram for s.s.b. receiver.

DETAILS OF DESIGN.

THE S.S.B. FILTER.

Demodulation of an s.s.b. signal is generally effected by beating the sideband with an oscillation inserted in the place of the original carrier frequency. Signals appearing on either side of this re-inserted carrier will be reduced to low frequencies and will be indistinguishable. For example, suppose an intermediate frequency of 500 kc/s is being used and that the wanted sideband lies between 500·3 kc/s and 503 kc/s. If at some instant a signal at 501 kc/s exists, the re-insertion frequency of 500 kc/s will produce the wanted output at 1 kc/s. If there is also a signal at 499 kc/s, due perhaps to an adjacent-channel unwanted signal, this will also beat with the 500 kc/s re-inserted carrier to produce an output at 1 kc/s. It is therefore necessary to precede the demodulator with a filter designed to pass only those frequencies lying between, in this case, 500·3 kc/s and 503 kc/s.

In a well-designed receiver selectivity should occur as near the receiver input as possible. This reduces the possibility of intermodulation between unwanted signals, or between wanted and unwanted signals. It is impracticable to make an s.s.b. filter tunable and hence it has to be placed after the first mixer stage.

The first intermediate frequency employed in a superheterodyne receiver must be outside the tuning range of the receiver. To maintain good rejection of the image channel the i.f. should be as high as is reasonably possible. For example, to tune a receiver over the range 2 to 30 Mc/s, an i.f. of 1·6 Mc/s (a 'standard' i.f.), would be reasonable. The image frequency occurs at a spacing of twice the i.f. (3·2 Mc/s) away from the wanted one, and even at 30 Mc/s it is possible to obtain fairly good rejection of a signal at 33·2 Mc/s.

The design of a filter for s.s.b. use becomes, in general, more difficult at higher frequencies. For a single speech channel the filter is required to pass a band of frequencies from about 300 c/s to about

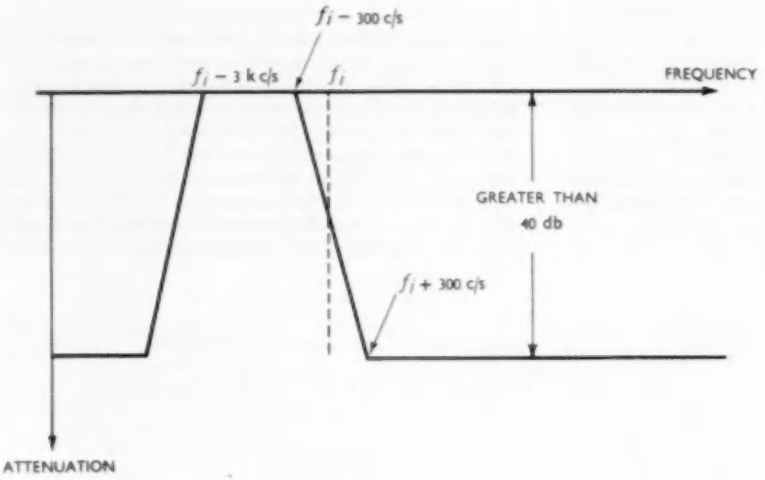

Fig. 5.—Required s.s.b. filter response for single-channel speech modulation.

3 kc/s relative to the intermediate frequency, and it is required to reject frequencies within a similar band on the opposite side of the carrier position. A rejection of at least 40 db should be achieved. Fig. 5 illustrates the type of frequency response curve which is required.

Basically there are three types of filter to be considered, *LC* filters, electro-mechanical filters and quartz crystal filters. The first become impracticable above about 100 kc/s and they are also relatively bulky. Electro-mechanical types have been manufactured in the U.S.A. for frequencies up to 455 kc/s, and in this country one firm is marketing units for use at 250 kc/s. The main difficulty in manufacture is in holding mechanical tolerances to very fine limits, and these limits become narrower as the frequency increases. For this reason it is unlikely that such filters will become available for higher operating frequencies, but in addition the temperature coefficient would prevent their use for s.s.b. work, where the overall variation should not exceed about ±50 c/s. Quartz, on the other hand, has a temperature coefficient at least one order lower.

In the past, receivers have used filters working at about 100 kc/s. To obtain reasonable image response it has therefore been necessary to employ two frequency changes in the receiver (a double superheterodyne). This type of receiver is not only more complex but will exhibit more responses to unwanted signals.

THE FREQUENCY SYNTHESIZER.

A frequency synthesizer is basically a signal generator whose frequency is continuously compared with, and corrected to, a standard frequency. In the present context, it is required to supply the local oscillator signal to the receiver to give sufficient accuracy of tuning for the reception of s.s.b. suppressed - carrier signals. For this use the synthesizer output has to be of high purity, that is, free from components at any frequency other than the wanted one. It will be appreciated that if an unwanted component is present in the output, a signal input to the receiver at the appropriate frequency could beat with this component to give the correct intermediate frequency. This i.f. would be indistinguishable from the wanted i.f. and could form a serious source of interference, particularly if the unwanted signal was much larger than the wanted one.

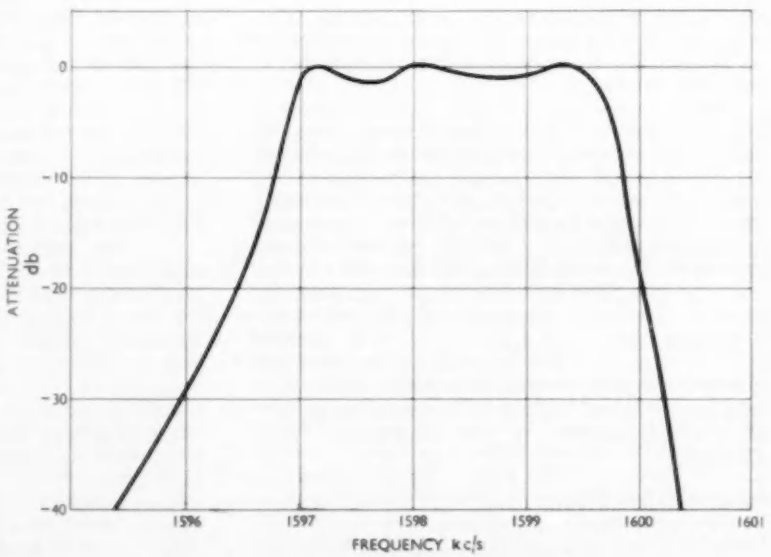

Fig. 6.—Frequency curve of prototype s.s.b. crystal filter.

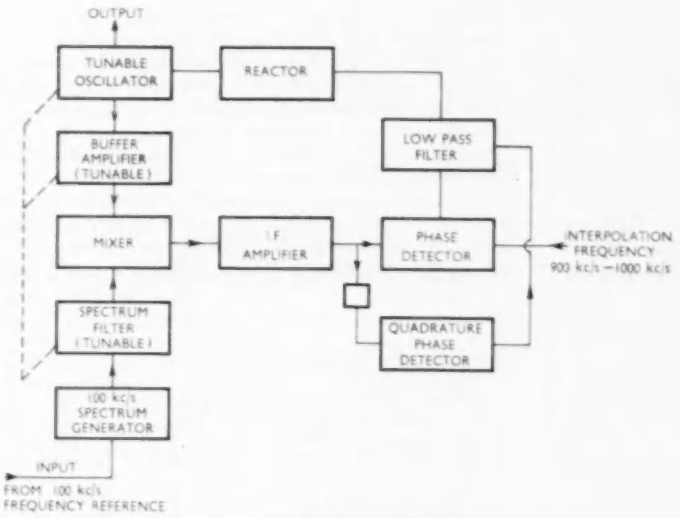

Fig. 7.—Basic synthesizer block diagram.

OTHER FORMS OF S.S.B. RECEIVER.

The general form of receiver described is not the only method of receiving s.s.b. signals. Another method is to use a multi-stage superhet. form shown in fig. 8. Here the synthesizer is in effect integrated with the signal channel and each local-oscillator signal is derived by frequency multipliers and dividers from the standard frequency source. The successive intermediate-frequency amplifiers operate at lower frequencies and have narrower bandwidths. Depending on the accuracy of tuning required, the local oscillators need not all be referred to the standard frequency. Once the operating frequency is sufficiently low, the inherent stability of the oscillator may be good enough.

A third system which may be used is the Wadley or Triple Mix System. A block diagram of this system, suitable for h.f. use, is shown in fig. 9. The catalytic oscillator is required to be set in steps of one megacycle and it is used to convert the signal frequency to an i.f. of 40 Mc/s. It also converts a line in a one megacycle spectrum to pass through a 37·5 Mc/s filter. The 40 Mc/s and 37·5 Mc/s filter outputs are combined in a further mixer to produce a 3-2 Mc/s output. Since the same local oscillator, the catalytic oscillator, is used in the signal channel and the spectrum channel, any inaccuracy in its tuning cancels out. The signal has therefore been translated to the 2-3 Mc/s band by an integral number of megacycles with the accuracy of the reference frequency standard. This process may be followed by a similar unit operating from a 100 kc/s spectrum, and so on down to a frequency such that local oscillator stability is good enough for satisfactory demodulation.

Wide-band mixer circuits are used in both these systems, and such circuits give rise to many spurious responses. For exceptional performance in this respect the receiver system described earlier and shown in fig. 2 is to be preferred.

GENERAL COMMENTS.

Two major advantages for s.s.b. communication were mentioned earlier. There are other advantages, such as relative freedom from selective fading, and the

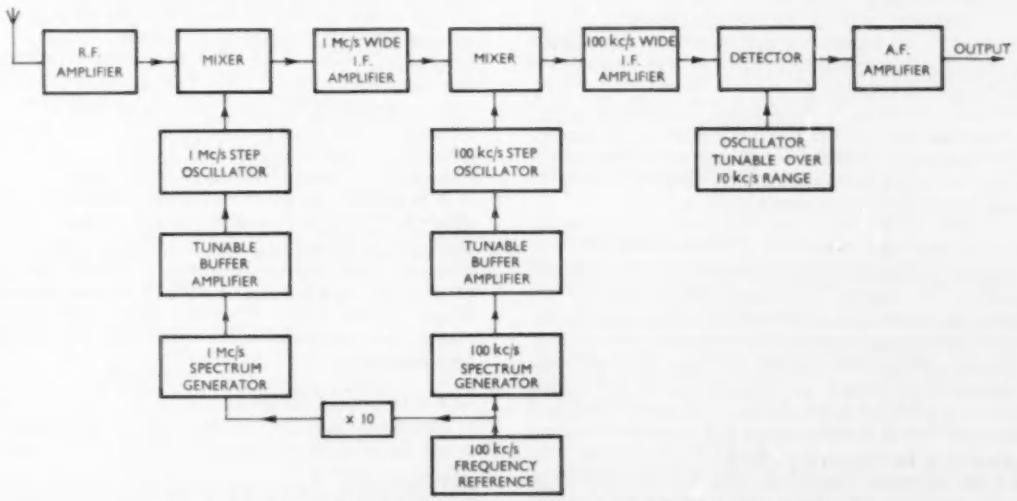

Fig. 8.—Block diagram of multi-stage superhet, combining synthesis and signal channels.

ability to convey two independent wide-band channels from one transmitter by using independent sideband modulation—here both sidebands are transmitted, each having different information content. These advantages have to be compared with the disadvantage of complex receiving equipment.

Where communication over only a few fixed-frequency channels is wanted, the additional complexity of the receiver is small. For air-to-ground communication the increase in transmitter efficiency may easily outweigh the disadvantages. The aircraft equipment can be simplified by the use of automatic frequency control of the ground transmitter and receiver to align the ground equipment to the aircraft's relatively unstable apparatus.

Fully tunable systems, referred to synthesizers, can be used where security is important. Using a pre-arranged frequency schedule, short messages could be passed using a suppressed carrier radiation with little fear of their being satisfactorily demodulated by any but the most complex apparatus.

indicate when phase lock occurs, and to switch in a narrow band filter which ensures good noise immunity and rigid locking. This two-mode operation permits fast pull-in to lock, and purity of output when locked.

The operation of the synthesizer is best illustrated by considering how a particular frequency is set up. The 3·6 to 31·6 Mc/s oscillator is first set as closely as possible to the desired frequency. The interpolating oscillator is adjusted to give the tens of kc/s downwards. For example to obtain 22·1357 Mc/s, the tunable oscillator should be set to about 22·13 Mc/s, and the interpolating oscillator to 900 + 35·7 kc/s. The tunable oscillator

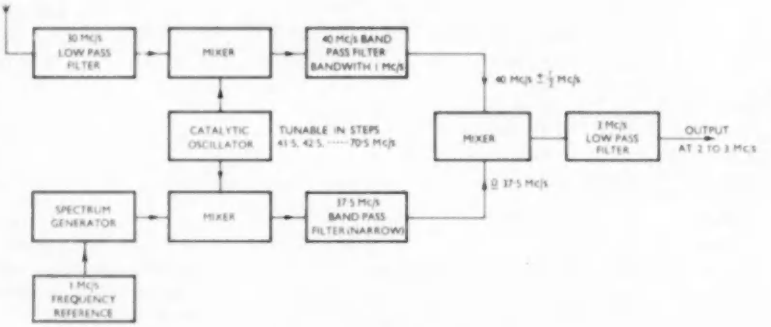
30 Mc/s LOW PASS FILTER
MIXER
40 Mc/s BAND PASS FILTER BANDWITH 1 Mc/s
40 Mc/s ± ½ Mc/s
CATALYTIC OSCILLATOR
TUNABLE IN STEPS 41·5, 42·5, ... 70·5 Mc/s
MIXER
2 Mc/s LOW PASS FILTER
OUTPUT AT 2 TO 3 Mc/s
@ 37·5 Mc/s
SPECTRUM GENERATOR
MIXER
37·5 Mc/s BAND PASS FILTER (NARROW)
1 Mc/s FREQUENCY REFERENCE

Fig. 9.—Triple-mix principle.

RECENT DEVELOPMENTS.

Studies of the problems associated with the design of s.s.b. suppressed-carrier receiving equipment have led to the development of a frequency synthesizer with exceptional characteristics and to the design of an automatic frequency control system for operation with a voice controlled, or floating, carrier system. Here the carrier component is only occasionally transmitted. Correction is achieved rapidly at the receiver and the correcting voltage maintained until more carrier information appears.

Automatic gain control when no carrier component is present is another aspect which has been studied and new circuits developed.

For h.f. operation it was decided to design a quartz crystal filter for 1·6 Mc/s. Two filters, one for the upper sideband, the other for the lower sideband, will shortly be available. A frequency response curve of one of the prototypes is shown in fig. 6.

DETAILS OF THE FREQUENCY SYNTHESIZER[1].

A basic design has been evolved which is capable of providing an output of greater purity than 80 db (0·01% in amplitude) for non-harmonic components. A block schematic diagram is shown in fig. 7.

An output from the tunable oscillator is mixed with a harmonic spectrum so that an i.f. in the region 900 kc/s to 1000 kc/s is produced. This is amplified and compared with a similar frequency, injected from an interpolating oscillator, in a phase detector. The output from the phase detector is then used to control the tunable oscillator via a filter and reactance valve stage. A second phase detector fed in quadrature is used to

should have a setting accuracy of better than about 30 kc/s. The 22·13 Mc/s output will beat with the 100 kc/s spectrum in the mixer to form an i.f. in the range 900 kc/s to 1000 kc/s. This will beat with the 935·7 kc/s interpolation signal in the phase detector and produce a control voltage, which will lock the tunable oscillator onto the appropriate 100 kc/s harmonic plus the 35·7 kc/s interpolating frequency.

This phase-locked unit can be used as a basis for various types of complete synthesizer. If a frequency accuracy of one or two cycles per second is required the interpolating frequency can be derived from a similar phase-locked loop operating from the same frequency standard. Alternatively, pure synthesis methods or individual quartz crystals, or a combination of the two, may be used for interpolation.

When the frequency accuracy required falls to about ±50 c/s, it is possible to use a decade type *RC* oscillator operating over the range 10 kc/s to 110 kc/s. The output of this is translated to the required 900-1000 kc/s range using a signal derived from the frequency standard. Whatever system for interpolation is used the purity of the synthesizer output would be maintained.

ACKNOWLEDGEMENT.

The work described in this article was carried out under an Admiralty Contract.

REFERENCES.

1. Carnt, P. S. and Richester, E: The Synthesis of High Purity Oscillations Suitable for S.S.B. Receivers. Paper presented at the Brit. I.R.E. Symposium held on 25 May, 1960.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

THE EFFECT OF IMPURITIES ON THE GROWTH OF SYNTHETIC QUARTZ (751).*

By C. S. Brown and L. A. Thomas (Research Laboratories).

J. Phys. Chem. Solids, Vol. 13, *No.* 3/4, *pp.* 337-343. *Pergamon Press*, 1960.

An investigation has been carried out aimed at developing a process for the growth of large crystals of synthetic quartz using silica-rich rocks native to the United Kingdom as the raw material. As a result of this work the effect of impurities on the habit and quality of the crystals has been determined. The role of aluminium as a key impurity has been proved and the darkening produced by X-irradiation has been used to study the distribution of impurities in the synthetic quartz. Recent work has thrown further light on the manner in which aluminium, possibly associated with another element, is incorporated in the quartz structure.

THE USE OF SEMICONDUCTOR DEVICES IN P.A.M. SYSTEM DEMODULATION (838).*

By J. N. Barry and F. J. Nixon (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 16, 1959.

The paper discusses the design and engineering details of two types of demodulator equipment which will operate from a p.a.m. system, and could be used, for example, in the field of electronic telephone exchanges. Apart from normal circuit-elements the equipments contain only semiconductor diodes and transistors. The equipments described will provide electrical characteristics conforming to different levels of performance such as might be required for local or trunk routing. They are both designed to operate on a 100-channel system and will provide gain of the signal information of about 40 dB.

EMITTER EFFICIENCY AND INJECTION LEVEL IN DIFFUSED STRUCTURES (841).*

By A. K. Jonscher (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 15, 1959.

The differential equations governing the transport of injected carrier densities in inhomogeneous semiconductors are set up and solved for low and high injection levels. The solutions are applied to the flow of current in the base and emitter regions of transistor structures obtained by solid-state diffusion techniques. This leads to the establishment of the criteria for the onset of high-injection conditions which entail the limitation of the speed of response. The analysis indicates the optimum structural parameters for a fast-response high-current diffused transistor.

STABILITY CONDITIONS IN TUNED COMMON-EMITTER TRANSISTOR AMPLIFIERS (849).*

By G. Phylip-Jones (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 15, 1959.

Some of the important factors which determine the stability of common-emitter tuned amplifiers are discussed. It is shown that the minimum value of feedback capacitance required to produce instability depends on the number of stages in the amplifier and that it varies appreciably with the phase shift in the transistor.

In any particular case two values are obtained corresponding to whether the circuit is under- or over-neutralized, and these values define the boundaries of the stability region. At frequencies very much lower than the α-cut-off frequency of the transistor, these two limits are equal in magnitude, but as the frequency is increased there is an increasing difference between them.

SECTIONING AND FAULT ANALYSIS OF JUNCTION TRANSISTORS (850).*

By B. A. I. Davis and D. L. Lynton (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 15, 1959.

Special techniques have recently been developed by the authors to enable microsections to be readily made on high-frequency *p-n-p* and *p-n-i-p* junction transistors. It is impossible to use standard metallographic techniques when sectioning these devices, owing to the extreme fragility of the very thin germanium wafers used in their fabrication.

The paper describes the preparation of large numbers of sections on a routine basis, using these techniques, and a number of examples are shown and typical faults discussed.

RADAR CRYSTAL VALVES (854).*

By A. Lindell and T. Oxley (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 15, 1959.

A brief historical survey is made of the use of semiconductor devices as frequency changers or mixers in radar applications, with particular reference to factors that led to the design and performance of the types CV2154-5 silicon mixer crystals. A mixer crystal incorporating a germanium wafer and titanium whisker is described.

The necessity for positive bias, its effects on r.f. admittance and noise factor and methods of obtaining the bias when required are considered.

Finally, it is shown that the behaviour of germanium mixer crystals as a function of temperature is not significantly different from silicon devices.

A PULSE-CODE MODULATOR USING JUNCTION TRANSISTORS (858).*

By A. J. Armstrong (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 16, 1959.

This paper describes a pulse-code modulator, using junction transistors, designed to provide a 5-digit transmission of a signal having a total bandwidth of 800 c/s. The system described uses the pulse-count method as being the most straightforward way of producing a digital code from an a.c. waveform. A monitor unit is included to decode any required number of digits of the output signal so that system-evaluation tests can be carried out.

Temperature tests are also described, the results of which show that the equipment will operate satisfactorily up to a temperature of at least 65° C.

VALIDITY OF THE THEORY OF DOUBLE STREAM AMPLIFICATION (881).*

By D. T. Swift-Hook (Research Laboratories).

The Physical Review, Vol. 118, *No.* 1, *pp.* 1-5, *April*, 1960.

Misunderstandings have recently arisen concerning the validity of the original analysis of the interaction between interpenetrating ion streams to give double stream amplification. It is shown that none of the modes of propagation upon which criticism has been centred corresponds to that of double stream amplification. A direct theoretical proof of the validity of the theory is given.

ENVELOPE DESIGN FOR SEMICONDUCTOR DEVICES (888).*

By A. Lindell (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 15, 1959.

Semiconductor devices have high-current low-voltage characteristics, are very temperature dependent, are basically very small and robust and must be hermetically sealed. Further, they cover a frequency range up to about 100 Gc/s, voltages up to thousands of volts, currents up to hundreds of amperes and a temperature range of the order of −200° C. The effect of these factors on the envelope design is discussed and the choice of metals and insulators for the envelope is considered. A strong case is made out for the extensive use of copper.

Finally, some thought is given to mechanical standardization of outline dimensions of semiconductor devices with similar electrical characteristics made by different manufacturers.

POTENTIAL DISTRIBUTION BETWEEN TWO PLANE EMITTING ELECTRODES (894).*

By P. A. Lindsay and F. W. Parker (Research Laboratories).

Journal of Electronics and Control, Vol. 7, *No.* 4, *p.* 289, *October*, 1959.

This paper gives the derivation of expressions for the space charge and potential distribution between two plane parallel emitting electrodes. Numerical calculations are carried out for the case when an external potential difference is applied between the electrodes, both being at the same temperature. It is shown that all possible potential distributions can be represented by a single family of curves.

R.F. SPECTRA OF WAVES FREQUENCY MODULATED WITH WHITE NOISE (899).*

By R. G. Medhurst (Research Laboratories).

The Institution of Electrical Engineers, Monograph No. 380*E*, *May*, 1960.

Although comprehensive sets of curves are available giving the radio-frequency spectra of waves phase modulated with band-limited white noise (simulating f.d.m. telephony signals), the corresponding problem for frequency modulation turns out to be much more intractable. In the present paper the frequency-modulation problem is attacked using a method employed in an earlier paper, in conjunction with numerical devices for improving the convergence rate of very slowly converging series. The results are presented as a set of curves covering the range of modulation parameters likely to be encountered in trunk radio systems.

CALCULATION OF THE ELECTRONIC DENSITY AND COLLISION FREQUENCY IN A DECAYING PLASMA (900).*

By T. L. Dutt and A. G. Stainsby (Research Laboratories).

Proceedings of the Fourth International Conference on Ionization Phenomena in Gases, Uppsala, 17-21 *August*, 1959.

Experimental results on the transmission of signals having frequencies ranging from 100 Mc/s to 10 000 Mc/s between probes external to a glass tube containing a decaying plasma yielded multiple resonances. When the frequencies at which these resonances were plotted of time, it was observed that they lay on one of four lines.

An attempt has been made to explain these resonances in terms of the complex conductivity and complex dielectric constant of the plasma. These quantities have been derived from the simple equation of motion of the electron in a plasma, terms describing collision damping and space charge being included.

THE NOISE AND GAIN PROPERTIES OF MOLECULAR AND PARAMETRIC AMPLIFIERS (909).*

By E. D. Farmer (Applied Electronics Laboratories).

Journal of Electronics and Control, Vol. 7, *No.* 3, *p.* 214, *September*, 1959.

The chief advantage of using a molecular or parametric amplifier in a microwave receiver lies in the possibility of obtaining a low overall noise figure as compared with systems using travelling-wave tubes or other electron-beam devices where the presence of shot noise sets a considerable limitation on noise performance.

In this article the noise and gain properties of a cavity amplifier are analysed with sufficient generality so as to include both the 'Maser' (molecular amplifier) and the parametric amplifier as special cases. This unification is achieved with the aid of the concepts of negative noise temperature and negative quality factor.

In particular the three-level Maser of Bloembergen and the ferrimagnetic amplifier of Suhl are discussed in some detail. In conclusion it is shown that the results may be used to design an amplifier having optimum low-noise performance.

HOLE CONDUCTION AND PHOTOVOLTAIC EFFECTS IN CdS (910).*

By J. Woods and J. A. Champion (Research Laboratories).

Journal of Electronics and Control, Vol. 7, *No.* 3, *p.* 243, *September*, 1959.

Semiconducting crystals of CdS have been prepared in which the conduction current is carried preponderantly by positive holes. This is indicated by the positive sign of the Hall voltage and the thermoelectric power. The preparation of these crystals, which were heavily doped with 1–2% Cu, is described. Measurements of electrical conductivity, Hall coefficient and thermoelectric power over the temperature range 95–380 K are reported. The results are difficult to interpret, but suggest that conduction occurs via impurity levels due to copper.

PRINCIPLES OF THERMOELECTRIC DEVICES (919).*

By H. J. Goldsmid (Research Laboratories).

British Journal of Applied Physics, Vol. 11, *No.* 6, *pp.* 209-217, *June*, 1960.

In recent years, the use of semiconductor thermojunctions has improved the efficiency of generation by means of the Seebeck effect and has made thermoelectric refrigeration a practical possibility. By using semiconducting compounds of high mean atomic weight, Seebeck coefficients of about 200 μV/° C have been obtained without the ratio of electrical to thermal conductivity departing too far from the value given by the Wiedemann-Franz law for metals. The most favourable semiconductors have been improved still further by alloying with isomorphous materials. Devices employing the thermoelectric effects are discussed.

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